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The first issue of the journal "Podzemni radovi" (Underground Mining Engineering) was published back in 1982. Its founders were: Business Association Rudis - Trbovlje and the Faculty of Mining and Geology Belgrade. After publishing only four issues, however, the publication of the journal ceased in the same year.

Ten years later, in 1992, on the initiative of the Chair for the Construction of Underground Roadways, the Faculty of mining and Geology as the publisher, has launched journal "Podzemni radovi". The initial concept of the journal was, primarily, to enable that experts in the field of underground works and disciplines directly connected with those activities get information and present their experiences and suggestions for solution of various problems in this scientific field.

Development of science and technique requires even larger multi-disciplinarity of underground works, but also of the entire mining as industrial sector as well. This has also determined the change in editorial policy of the journal. Today, papers in all fields of mining are published in the "Underground Mining Engineering", fields that are not so strictly in connection with underground works, such as: surface mining, mine surveying, mineral processing, mining machinery, environmental protection and safety at work, oil and gas engineering and many others.

Extended themes covered by this journal have resulted in higher quality of published papers, which have considerably added to the mining theory and practice in Serbia, and which were very useful reading material for technical and scientific community.

A wish of editors is to extend themes being published in the "Underground Mining Engineering" even more and to include papers in the field of geology and other geo-sciences, but also in the field of other scientific and technical disciplines having direct or indirect application in mining.

The journal "Underground Mining Engineering" is published twice a year, in English language. Papers are subject to review.

This information represents the invitation for cooperation to all of those who have the need to publish their scientific, technical or research results in the field of mining, but also in the field of geology and other related scientific and technical disciplines having their application in mining.

Editors

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Original scientific paper

ROBOTICS IN UNDERGROUND COAL MINING: ENHANCING EFFICIENCY AND SAFETY THROUGH TECHNOLOGICAL INNOVATION

Parankush Koul[1]

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Abstract: The aim of this paper is to explore how robotics can be applied to underground coal mining in order to make operations more efficient and safer with the help of technology. It calls for the use of regulations developed by industry bodies including the National Institute for Occupational Safety and Health (NIOSH) and the Mine Safety and Health Administration (MSHA) to ensure that robotics are used safely and efficiently in mining. The study also points to NIOSH efforts to resolve health and safety issues around automation technology in the mining industry. When high-tech robotic equipment is deployed, it demonstrates great productivity gains and less human suffering from disease. In demonstrating these innovations, the paper proposes that robotics must be continually innovated to maximize extraction of resources and worker safety, positioning robots as the new force in the coal mining industry.

Keywords: Robotics, Automation, Safety, Efficiency, Technological Innovation

1 INTRODUCTION

In underground coal mining, robots are now a game-changer, answering long-term safety, efficiency, and productivity issues. The use of sophisticated robotics is intended to minimize risks from the confined space underground, where manual work, in its conventional forms, can expose employees to toxic gases, falls, and extreme physical challenges.

With demand for coal extending across many industries, a better extraction strategy has never been more important. Robots and automation could maximize output because they could work uninterrupted in environments unsuitable or unsafe for human miners. It is intriguing to note that using robotic systems could also optimize multiple mining steps (from exploitation to transportation), significantly decreasing downtime and enhancing the yield (Mousavi et al., 2023).

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New technologies now have the capability to create self-driving mine trucks and robotic arms capable of drilling, chopping, and moving bulk materials with no human intervention (Shaffer and Stentz, 1992). They also enable data collection and processing, which allows for real-time monitoring for better decisions and safety.

And robotization of coal mining is a chance to fill the skills shortage and job deficit within the industry. When the older generation of miners retires, robots enable us to keep up with operations without overreliance on humans (Evgeny and Anatol'evna, 2020). Such automation movement is considered a necessary move towards maintaining productivity in an era of shifting workforces and regulatory demands regarding work-related safety (Lien, 2013).

Coal mining robotics is also fueled by the research and development in collaboration between industry, government, and academia to improve robotic applications and to create new solutions for the specific needs of the underground mining operations (Xusheng, et al., 2018a). Through these developments, coal mining is now prepared to transition into an intelligent, safer, and more effective way of working that, in turn, will redefine productivity and worker safety standards in the industry.

2 CURRENT APPLICATIONS OF ROBOTICS IN UNDERGROUND COAL MINING

Through safety, efficiency, and productivity, underground coal mining has become more and more transforming into robotics. Different types of robots and their functions are now absolutely required for the unique problem in this field.

2.1 Types of Robots Used in Underground Coal Mining

Robotic systems have been built for different needs of underground coal mining. These are the usual robot types:

- Autonomous Mining Machines: The machines will operate without humans in hostile conditions. The U.S. Bureau of Mines has been developing automation in conjunction with continuous mining machines to build self-guiding and safe autonomous machines (Welsh, 1989).

- Drilling Robots: Drilling robots help in building mine tunnels by controlling trajectory complexity brought on by complex rocks. Such robots can change drilling routes in real time based on the information provided by the strata below (Rathore and Srivastav, 2018).

- Robotic Mining Equipment: Coal mine robots (CMRs) have position technology, such as ultra-wideband (UWB) sensors. These robots are deployed for high-accuracy localization and operation in restricted underground space (Wormald, 2014).

- Teleoperated Robots: Remotely operated robots help inspect and maintain things at risky sites. They make things safer because there's no longer a direct human presence in dangerous places (Valverde, 2024).

2.2 Examples of Robotic Functionalities

The robot capabilities of underground coal mining are different and designed for better operation. Some notable examples include:

- Localization and Navigation: With UWB technology and inertial measurement devices, CMRs are very precise in localizing. This permits efficient tracking in the steep subsurface conditions by making up for the lost signals and multipath jitter (Wormald, 2014).

- Automation of Mining Operations: With the use of intelligent sensors and self-directing navigation systems, mining machines can handle high-level tasks with low human presence. Whether it is material movement, mining, or site surveying, which are all performed under close surveillance of safety requirements (Welsh, 1989).

- Data Collection and Analysis: Robotics usually come with a variety of sensors (e.g., sonar, laser rangers) that help collect data in real-time. This assists with monitoring structure health and efficiency as well as decision-making due to greater insight into underground conditions (Duddu, 2024).

- Safety Enhancements: When robotics are employed to perform dangerous tasks like mining coal and inspecting machinery, the human worker's exposure to the environment is dramatically reduced and safety is increased (Welsh, 1989).

3 IMPLEMENTING ROBOTICS IN UNDERGROUND COAL MINING: STEPS TO ENHANCE EFFICIENCY AND SAFETY

The introduction of robots into subsurface coal mining is part of a complex solution to improve efficiency and safety in a very dangerous industry. We describe below the essential steps of this implementation process.

- Assessment of Current Mining Operations: Before applying robotic systems, an analysis of the existing mining process is necessary. These include a review of the technology, safety, and operating problems at the current levels of underground coal mining. Figuring out what the requirements and constraints of the existing processes are will guide the development of suitable robots (Wang et al., 2014).

- Selection of Appropriate Robotic Systems: The next step is to choose the right robotic technologies to meet the needs identified. Robotics of all kinds could be used: self-driving cars to move the material, robot drills, and drones for surveillance and monitoring. These should be chosen on the basis of capability, interoperability with other machinery, and ability to boost productivity and security (Kolapo, 2024).

• Design and Testing of Robotic Solutions: After robotic systems are chosen, the prototyping and design process takes place. This includes software and hardware design and sensors and control systems integration that are required to operate in the mining area on a real-time basis. It is essential to test these systems under virtual conditions thoroughly to be sure that they are safe and reliable (Kolapo et al., 2024). Also, it is during this testing phase to adjust it iteratively on the feedback of performance.

• Integration with Mining Operations: The integration of robotic systems into existing mining operations must be managed carefully. This means integrating robots with humans and older machines. This fusion can also include upgrades to the existing infrastructure and a new protocol for operation to enable cooperation between robots and human workers (T.E. et al., 2018).

• Workforce Training and Change Management: The adoption of robotics requires the employee to be trained in how to adapt to the new technology. They are trained to run the robot systems, know what they can and cannot do, and to follow the new safety regulations. Change management methodologies must be applied to manage any hesitance and promote knowledge of the benefits of robotics for improving safety and effectiveness (Li et al., 2019).

• Continuous Monitoring and Evaluation: Once robot systems are placed in place, their performance needs to be continuously monitored and evaluated. This step involves collecting information on the efficiency, accidents, and overall performance of the robot systems. Mining operations can then evaluate these data and decide what needs improvement or system changes (Trevelyan et al., 2016).

• Safety Considerations: Robotics will make underground coal mining much safer by taking on the dangerous tasks and leaving workers less exposed to risk. Safety features such as emergency braking, collision avoidance, remote control, and so on should be part of any robot design (Gaokgorwe, 2023). But also, safety training for humans on the interaction and operation of robots should be provided.

• Feedback Loop for Continuous Improvement: Creating a feedback loop for all engineers, operators, and safety staff to continue improving is possible through a feedback loop. With periodic review and update according to operations experience and technological advancement, mining operations will remain safe and successful (Du et al., 2023).

4 KEY INDUSTRIAL STANDARDS FOR ROBOTICS IN UNDERGROUND COAL MINING

There are many regulations governing the underground coal mining robots to make sure that they work safely and effectively. Organizations like the NIOSH, the MSHA, and the International Organization for Standardization (ISO) have issued regulations regarding robotics.

4.1 NIOSH Standards

NIOSH has also undertaken research programs on the health and safety of automation and robotics in mining operations. Key points include:

- Automation and Robotics Research: NIOSH's research is focused on the detection and prevention of health and safety risks associated with mining automation technologies.
- Proximity Detection Technologies: NIOSH suggests proximity detectors in order to maintain the safety of mobile robots in the underground (NIOSH, 2019).

4.2 MSHA Standards

The MSHA enforces standards crucial to the mining robotics' safety. Important rulings include:

- Proximity Detection Systems: MSHA mandated in 2015 that continuous mining machines with proximity detectors meet performance criteria (Mine Safety and Health Administration, 2015). These controls are essential to avoid miners and machinery accidents.
- Training Requirements: MSHA's law requires miners who work on or near automation equipment to be trained in the safety procedures associated with these systems. Including in case of emergencies and knowing the technical details of proximity detection (MSHA Safety Services, 2023).

4.3 ISO Standards

ISO has produced some very relevant standards for the safety and operation of automated machinery in mining:

- ISO 17757: It covers safety standards for autonomous and semi-autonomous earthmoving and mining machines. It defines safety standards for machines and systems related to them, including hardware and software (ISO, 2019).
- ISO 10218-1 and ISO 10218-2: These specifications stipulate fundamental safety requirements for industrial robots and specify protective precautions for

their safe integration and operation (ISO, 2011a; ISO, 2011b). They focus on risk reduction approaches and are common globally, in the United States as ANSI/RIA R15.06.

4.4 American National Standards Institute (ANSI) Standards

The ANSI offers standards for mining industrial robots in the form of standards like:

- ANSI/RIA R15.06-2012: This is the standard specifying safety for the manufacture, installation, and use of industrial robots and systems, and in other words, is a must-have standard for mining robotics in order to ensure the safety of workers (ANSI, 2012).
- Technical Reports: ANSI also has technical reports, which provide information on specific topics about industrial robots such as risk analysis, protecting processes, and cooperative robot safety (Occupational Safety and Health Administration (OSHA), n.d.).

5 COMPANIES EMPLOYING ROBOTICS IN UNDERGROUND COAL MINING

Using robotics to mine coal underground has a lot of advantages for both efficiency and safety. Following is a detailed list of ten companies utilizing robotic technologies in this niche, highlighting the specific innovations they employ.

5.1 Komatsu

Komatsu is the world’s leader in robot coal mining and their automated systems that maximize safety and efficiency. Their Longwall Command and Control solution lets mining machines be remotely managed without personnel having to face the elements (Valverde, 2024). This technology makes operations more stable and reduces human exposure to hazardous environments. And the AFC Faceboss RS20s control system (launched in August 2022) that will provide safety and operational synergy for longwall coal production (Duddu, 2024).

5.2 Sandvik

Sandvik has set the standard for mining automation with its AutoMine® platform for autonomous, remotely operated mining machines. The system enables the operator to control several machines remotely for a lot more safety and efficacy (Sandvik AB, 2024a). And, Sandvik's recent acquisition of Universal Field Robots (UFR), which adds automation solutions for various types of equipment (Sandvik AB, 2024b; Stutt, 2024).

5.3 Caterpillar

Caterpillar's robotic solutions converge on automation for safety and productivity. Their underground mining robots allow them to work from afar, keeping the operations within sight (Duddu, 2024). Trucks and drilling rigs driven by robots eliminate human presence in risky places (Allawadhi, 2024).

5.4 China Energy Investment

China Energy Investment applies autonomous technologies to mining to increase productivity and safety. They use their systems for automated haulage and drilling to reduce both time and injuries. The automation of robots decreases operational costs and working conditions (Duddu, 2024).

5.5 Tian Di Science & Technology

Tian Di Science & Technology develops intelligent mining solutions such as coal production automation. Their robots control and observe mining activities to eliminate accidents in tight spaces. Such technologies also automate processes and increase recovery rates by maximizing extraction of resources (Duddu, 2024).

5.6 Shanxi Tiandial Mining Machinery

Shanxi Tiandial Mining Machinery has rolled out automation systems for optimal performance in underground coal mining. Their robots have automated drilling tools, which make it less painful for employees and safer (Duddu, 2024). The addition of robotics also ensured drilling more accurately with less waste.

5.7 Deere & Co

Deere & Co. has developed robot technologies for safer and more productive mining. They have solutions such as self-driving vehicles that eliminate the human workers in the underground environments (Duddu, 2024). These technologies add safety ratings to the overall mining performance and also improve efficiency (Allawadhi, 2024).

5.8 Famur Group

Famur Group is a mining equipment company, and they have developed robotic solutions to ensure safer and more efficient coal mining operations. They provide automated coal handling and logistic systems to reduce risk from the conveyor system (Duddu, 2024). Their systems make the environment safer to operate by eliminating manual operations (Allawadhi, 2024).

5.9 Shanghai Chuangli Group

Shanghai Chuangli Group manufactures robots for underground coal mining. Their automation ensures that the hazards of manual labor in a dangerous environment are minimized and the accuracy of mining increased (Duddu, 2024). This attention to safety means higher production rates and healthy workers (Allawadhi, 2024).

5.10 UFR

UFR is an autonomous mining solution that was acquired by Sandvik for surface and underground mining. Their interoperable systems interface with any kind of mining equipment to allow an entirely automated mining operation, which is safe and efficient. The combination is said to be efficient and expands the power of current mining systems (Stutt, 2024).

6 LITERATURE REVIEW ON APPLICATIONS OF ROBOTICS IN UNDERGROUND COAL MINING FOR ENHANCING EFFICIENCY AND SAFETY

The number of articles covered in this review for the applications of robotics in underground coal mining for enhancing efficiency and safety are shown in Figure 1 from 2015 through 2024.

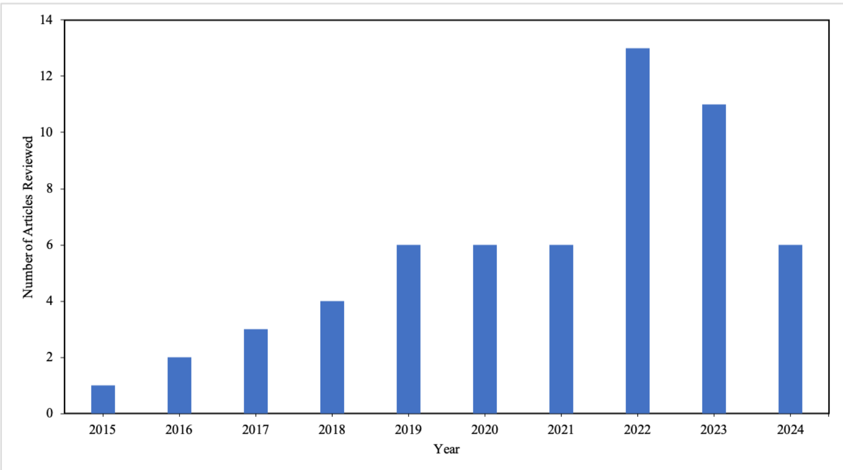

Figure 1 Articles reviewed (2015-2024) for applications of robotics in underground coal mining for enhancing efficiency and safety

Table 1 below shows a quantitative distribution by publisher of the number of articles related to robotics in underground coal mining for enhancing efficiency and safety.

Table 1 Number of articles from different publishers reviewed for robotics in underground coal mining for enhancing efficiency and safety

Publisher	Number of Articles Reviewed
IEEE	12
MDPI	7
Springer	7
EDP Sciences	6
IOP Publishing	3
Australian Centre for Geomechanics (ACG)	2
Elsevier	2
Wiley	2
Advanced Information Systems	1
Advances in Geo-Energy Research (AGER)	1
AGU	1
Association for Computing Machinery	1
Canadian Science Publishing	1
Clausius Scientific Press (CSP)	1
IAARC	1
IJAICT	1
ISPRS	1
Sage Journals	1
Scientific Research	1
SPIE	1
SSRG International Journals	1
SSUGT	1
Taylor & Francis	1
The Southern African Institute of Mining and Metallurgy	1
Universitas Mercu Buana	1
Total	58

6.1 Robotics in Underground Coal Mining: Technological Innovations for Enhanced Safety and Operational Efficiency (2015-2020)

Prashanth and Lelinadevi (2015) worked on a wireless robot with a mixed-signal processor (MSP430) to guide and scan for poisonous gases in coal mines without human supervision, addressing safety issues like obstacle avoidance, poisonous gas detection, and extremely low power consumption (compared with previous systems based on the 8052 microcontroller and ZigBee). Marshall et al. (2016) provided a general overview of mining robotics, writing about how the industry has integrated robots in all areas of mining operations (such as excavation, hauling, and mapping). They focused on improvements in autonomous tramming, real-time fleet control, and mapping, such as simultaneous localization and mapping (SLAM), that could improve productivity and flexibility in shifting mine landscapes. Ledange and Mathurkar (2016) demonstrated an underground mine wireless monitoring and safety solution based on ZigBee communication that monitored ambient conditions, such as temperature, humidity, and toxic gases, in real time. Their construction was built to be cheap and minimally human, with the robot bringing safety by sending real-time data to a control room.

Ruiz-del-Solar et al. (2017) focused on advancing robotics for Chile's mining industry, emphasizing the automation of mining vehicles to build trust with local stakeholders, thereby enabling safer, more efficient operations. By contrast, Nikitenko et al. (2017) built robotic complexes designed to harvest minerals from steep coal seams and ore beds by taking away man-intensive labor in hazardous environments via unmanned machines. They showed how robots could adapt to dangerous, complex geological landscapes, increasing underground protection. Hargrave et al. (2017) focused on an infrastructure radar localization system for longwall coal mining. This system placed equipment in the right position with no additional infrastructure, which minimized workers' risks in underground spaces.

Jalas et al. (2018) proposed an information modeling (IM) framework for an underground laboratory to test and perform efficient use of automated machines used in tunnel construction and coal mining. They showed how IM can help with data management, collaboration, and testing in mining automation and robotics. Meanwhile, Xusheng et al. (2018b) looked at wireless communication requirements for coal mine rescue robots, describing electromagnetic wave propagation in rough underground environments. Their results, based on numerical simulations, showed how environmental factors like dust density and wall roughness affect signal attenuation, essential for robotic communication and operation in coal mines. Inozemtsev et al. (2018) went the safety route with an automated roof-distortion monitor for underground mines. They worked around the drawbacks of traditional monitoring and developed a sensor-based, data-led approach to constantly monitoring roof integrity in order to avoid accidents by detecting danger early.

Meshcheryakov and Meshcheryakov (2018) created an Automated Monitoring and Positioning System (AMPS) for coal mining excavators focused on angular orientation and operation times that allowed for control and operational management in open-cast mines. The industrial trial of the system showed that it worked, albeit at considerable expense and in complexity. Chakravorty (2019) analyzed the contribution of underground robots to mine safety by opening potentially dangerous or flooded sites to exploration and delivering real-time safety warnings, thus minimizing miners' exposure to risks. The results suggested that operational safety and efficiency would significantly improve, as robots could be more agile and precise, adding tools to the miners' arsenal.

Sakthi et al. (2019) developed an adaptive admittance control system for LHD's (load haul dumpers) in underground mining that automated the bucket control module to reduce the load time. They installed an autonomous loading controller (ALC) and put it through its paces in a simulation, confirming the system's capacity to respond dynamically to the mining environment, increasing productivity and safety.

Jones et al. (2019) explored the Hovermap autonomous drone, mainly for underground mine safety through remote inspection and data collection in dangerous areas. This drone deployed 3D SLAM that was able to operate in GPS-barred environments and glean ultra-high-resolution data to inform safety and efficiency enhancements, particularly by recognizing the behavior of rock masses and boosting production estimates. Meanwhile, Menendez et al. (2019) created the uSLAM autonomous underground robot solution based on ground-penetrating radar (GPR) and odometry. This technique applied a Rao-Blackwellized Particle Filter to make trajectory-based 3D occupancy grid maps to aid in navigation and hazard scanning for robots within deep subterranean environments. Klimov (2019) was devoted to electro-hydraulic shield support control systems for longwall mining. His studies looked at pressure distribution and the effect of longwall advance speed on shield load handling, with the goal of designing a shield to reduce safety risks and maximize coal extraction efficiency.

Wenjuan et al. (2019) compared the pose estimation of a boom-style roadheader using infrared LEDs and a monocular vision system to get accurate cutting-path localization even under low illumination and dusty conditions. This vision-based method (with a 16-point infrared target and P4P-based estimation) was very accurate, estimating to within 0.03 pixels, demonstrating that it is applicable for operational use in underground coal mining. Tauger et al. (2020) focused on creating a remote-control robot complex that would allow them to operate the mining at the surface, exposing human workers as little as possible to risk. This system used automated control using telemetry for both safety and operational efficiencies, enabling operators to remotely control equipment, and the research fitted into a global automation drive in mining. Kharlampenkov et al. (2020) studied the effects of labor productivity in coal mining by using a multiplicative model of the impact of automation and technology. It pointed out productivity gains from robotic systems, open-pit mining having better returns than underground mining, and looking ahead to the benefits of further technological innovations such as the 'Smart Mine' programs.

6.2 Advancements in Autonomous and Intelligent Robotics for Underground Coal Mining: Enhancing Safety, Efficiency, and Operational Control (2020-2022)

Mansouri et al. (2020) explored Deep learning autonomous navigation of Micro Aerial Vehicles (MAVs) in black mines by implementing a convolutional neural network (CNN) to steer the MAV and predict collisions, which enabled higher inspection and mining safety. By contrast, Woolmer et al. (2020) evaluated drone LiDAR in the

Olympic Dam Mine with Emesent's Hovermap to provide enhanced data collection and safety by reducing worker exposure to dangerous areas. This experiment demonstrated how long it takes and how high the volume of data can be achieved through progressively better training, showing how drones could potentially compete with traditional surveys in terms of accuracy and safety. Valuev and Volkova (2020) focused on the intelligent automation of unmanned coal mining, connecting neural networks for machine positioning, and designing intelligent control systems for unmanned mining. Their approach was to focus on regulating the fluctuating operating modes of mining machines to maximize machine agility and minimize human interference.

Protsenko et al. (2020) compared RRT-based pathfinding approaches (RRT, RRT-Connect, and RRT*) in difficult-to-reach underground spaces, such as mines. They found that RRT was best suited for optimal pathfinding, but RRT-Connect was best suited for rapid pathfinding tasks, making it important to choose algorithms in accordance with the actual work needs. Paredes and Fleming-Muoz (2021), on the other hand, analyzed the socio-economic impact of automation in mining and how increased robotics might boost efficiency, but they also caused serious concern over the displacement of jobs and the increasing inequality of workers' incomes. Their mixed-methods study revealed that lower-skilled occupations were more likely to be automated, while high-skilled ones could be boosted in wages, implying that robotics could have an uneven impact. Zheng et al. (2021) went technology-driven by combining LiDAR with an inertial navigation system (INS) to increase the positioning accuracy of longwall shearers. Their simulations showed that positioning errors were notably lower than traditional methods, and this helped automate and reduce risk in mining operations.

In their paper, Long Ma and Qing Chen (2021) studied underground charging safety of power batteries in CMRs by considering the energy exchange system and safety of flameproof chambers. They designed a detection experimental platform to check safety precautions while charging, resulting in a theoretical and experimental basis for better safety measures in deep, potentially explosive subterranean spaces. Instead, spearing et al. (2021) launched the SHURM (Safe Highwall Underground Remote Mining) approach that focuses on independent mining with continuous miners for operational reliability and safety. Their approach involved backfilling to avoid surface subsidence, and they demonstrated that a high rate of stable unsupported spans was possible when mined, offering a vast increase in extraction rates and environmental benefits compared with conventional methods. Meanwhile, Matloob et al. (2021) studied Artificial Intelligence (AI) or Machine learning based risk analysis in the coal mining industry. They reviewed statistics to find out which risks were most common and leveraged AI systems to enable real-time monitoring and predictive analysis, thereby increasing both efficiency and safety.

Su et al. (2021) focused on designing a self-learning path planner for the mining robots via stereo vision. These experiments enabled unmanned excavators to drive themselves through challenging quarry conditions, accurately identifying hazards and finding routes that would minimize energy and safety. Simulated using ROS and Gazebo, the research validated that the system worked effectively and had better performance during mining operations. The paper by Thivyabrabha et al. (2022) introduced an Internet of Things (IoT)-enabled robot that monitors mines for gases such as methane and carbon monoxide. This robot not only detected the threat from the environment but also assisted in rescue missions by providing real-time information via a web browser so that faster emergency response could occur. Its study revealed the potential to substantially improve miner safety through working under risky conditions without any humans present. Kumar et al. (2022) built a network of IoT-based safety monitors and warning systems in coal mines with multiple sensors to measure temperature, pressure, and gas levels, thus meeting the need for early warning technologies in coal mines. Their system prevented accidents by continuously monitoring the conditions and giving prompt warnings to miners and officials.

In "Autonomous Docking Using Learning-Based Scene Segmentation in Underground Mine Environments," Rajvanshi et al. (2022) built a vision-based autonomous docking solution for coal mine shuttle buses that uses an optimized RGBD camera to scan for obstructions in GPS-delimited environments. It showed better worker safety by eliminating risks arising from manual tasks, with the autonomous system able to recognize continuous miners and prepared safe routes with encouraging findings in controlled and experimental experiments. Conversely, Trybała et al. (2022) used a multi-sensor wheeled robot to 3D map mine tunnels and focused on sensor alignment to achieve navigation under GNSS-denied conditions. Their work was able to establish a robust calibration process that resulted in zero mean reprojection errors and very small uncertainties in extrinsic parameter calculations, suggesting the potential for increased productivity through precise mapping. Tishchenko and Vanag (2022) analyzed the broader potential of robots in solid mineral mining, finding particular areas of automation: excavation, drilling, and explosives processing. Their research revealed the need for proven robotics technology and predicted impacts on mining design and safety regulations, requiring both academia and industry to collaborate to solve the problems of robotics in mining.

Min et al. (2022) focused on the design of a hydraulic manipulator arm for an automatic bottom-laying robot, with a specific focus on how to minimize human exposure to unsafe environments through automation and fast module laying. The study described the robot's incorporated design, powered by explosion-proof diesel, and noted its capability for fine work essential to work in the subterranean. These findings showed significant enhancement in bottom-laying efficiency and hence coal mine safety. In contrast, Guo et al. (2022) addressed the requirement of a high-speed control system in coal mine inspection robots that were able to take over manual inspections. Their research showed that the currently available control systems were not real-time, so they proposed a new system with QT and RT-Thread. This experiment verified that the new control system dramatically improved the robot's real-time performance, stability, and simultaneous task execution required for effective mining under dynamic mining conditions. Castellanos-Ardila et al. (2022) focused on the safe application of autonomous and semi-autonomous machines (ASAMs) in subsurface mining. They devised techniques like the Operational Design Domain (ODD-UM) and System-theoretic Process Analysis (STPA) for addressing safety issues in the environment of ASAMs interacting with manually operated machines. The result offered a conceptual approach to make integration safe and thus drive efficiency and safety.

Wang et al. (2022) developed a collaborative control technique for an Excavation Support Robot (ESR) that facilitated much better positioning and posture corrections while mining. They used a mathematical formula incorporating the kinematic properties of the ESR and a sliding mode control algorithm to produce spectacular simulation results with position shifts under 0.10 m and posture changes that had a coordination error of -0.03 m. In a related article, Nanadrekar et al. (2022) described the introduction of robots to mining with Lidar sensors for self-driving vehicles and data acquisition in real time, resulting in enhanced safety in extreme conditions. They noted that the use of autonomous mobile robots (AMRs) for surveying abandoned mines marked an automated move, one that created efficiency gains and potentially saw robots take over humans' roles in mining. Meanwhile, Xue et al. (2022) focused on an advanced mapping approach using the LeGO-LOAM-SM algorithm with sophisticated loopback detection algorithms to increase environment perception in the idiosyncratic environments of underground mines. Their results showed a mapping accuracy of 0.01 m and an impressive reduction in data storage needs, thereby optimizing the performance of unmanned vehicles.

6.3 Advancements in Robotics and Automation for Enhanced Safety and Efficiency in Underground Coal Mining (2022-2024)

Dąbek et al. (2022) focused to automate a detection method of overheated idlers on belt conveyors with unmanned ground vehicles (UGVs) equipped with RGB and infrared imaging. They found that the detection algorithm was promising but was delayed in detection and refractory to temperature fluctuations and needed to be refined for environment-appropriate use. In contrast, Zhu et al. (2022) developed a better SLAM algorithm, which combined visual and inertial units for mobile robot navigation in coal mine tunnels. They showed that the technique had good localization and mapping performance under low illumination and uneven terrain, which is a successful way of autonomous navigation in rough terrain. Chenglin (2023) aimed instead at developing a robot arm with several applications for the repair of roads in confined space. It confirmed the mechanical arm's structural integrity using finite element analysis and identified design flaws for achieving better stability.

Aboelezz et al. (2023) focused on a fully safe drone propulsion system designed for the very unique dangers of underground coal mining. Their work exposed the challenges of meeting the stringent safety standards set by the MSHA and used computer modeling and experiments to overcome issues such as heat and airflow optimization to develop a more cost-effective drone that can ensure better mining safety. Guo (2023), by contrast, showed a smart cover robot with a novel cover-support system and pedrail that could move along any surface. The work involved testing the robot's moving parts and adding safety measures like gas identification to show that the robot could sustain safe operating pressures and stay safe while excavating coal. Ren et al. (2023) reported on a fully automated mine for very fine coal seams using sophisticated automation methods, such as automatic coal cutting and central control. The study was a comparative analysis and showed much efficiency and safety improvements over conventional techniques, especially when the working conditions are difficult.

Koval et al. (2023) worked on navigation for aerial robotic workers in challenging underground mine conditions. Their research had focused on the importance of human workers being picked up by drones, and therefore safety is one of the main consequences of their junction and human detection systems. The research concluded that it would help make coal mine operations safer and more efficient when successfully implemented. In contrast, Cheng et al. (2023) proposed an eye-directed drill pipe delivery automation for horizontal directional drilling rigs. Their work showed that, through the use of a 2D vision sensor and monocular vision, the robot's accuracy and reduced labor time were used in positioning drill pipes, making human errors and drilling operations safer. The CDC (2023) report gave a more general overview of robotics and intelligent mining technology, recommending that when combined, the robots and smart mining technologies not only reduced workplace accidents but also made operations more efficient through the automation of risky tasks. This was a review of technologies as well as case studies that demonstrated the benefits of robotics in mining, both in terms of safety and productivity.

The paper by Castellanos Ardila et al. (2023) focused on the integration of autonomous dump trucks in mixed traffic scenarios within underground mines. Its study was designed to establish operational safety through a method of argumentation that employed System of Systems (SoS) and STPA. Its conclusion was that an adequate safety case would make it easier for autonomous technologies to be accepted in the mining industry, so that more production could be generated while preserving safety. Jämsä-Jounela and Baiden (2023), by contrast, considered more broadly the use of robotics and automation in mining and mineral processing and the enabling effect of Industry 4.0 on operational efficiency. They found that the need for teleoperation and cloud IIoT platforms made data collection and decisions more responsive and safer and improved the efficiency of grinding and flotation operations. He et al. (2023) reported on new technologies and machinery to address risks in deep mining, especially rockbursts and gas bursts. It was a matter of collaborating across international boundaries on research that was necessary to create sophisticated safety systems and innovations in mining.

Leclerc et al. (2023) developed a tethered drone specifically for underground stop inspections called the NetherDrone. They worked to bypass the constraints of existing drones by using custom-designed ducted propulsion and a continuous power and communication tether, and their field tests showed they could make close-up lidar scans and sightings inside mine stops. Ayeisha and Anggoro (2024) looked more generally at the impact of digitalization in the coal mining industry at PT. X. Their study was conducted through interviews with executives to emphasize the need to integrate cutting-edge technology like automation, IoT, and drones to increase efficiency and address issues like high cost and reluctance by employees. They advised extensive training and communication to make the switch to automated systems. Fan (2024), by contrast, was more interested in the automated mining of hard-to-mine coal seams, with robotics assisting in the operation of automated machinery and fine-tuned control. He showed that such technologies could significantly reduce pollutant emissions and operations costs, all of which is beneficial for sustainable coal mining.

The study by Marathe et al. (2024) built a surveillance robot that would detect and track conditions in the field, greatly reducing the danger of gas leaks and earthquakes through wireless sensor networks. Their work successfully showed how mobility, visual monitoring, and other environmental sensors can be combined to enhance safety protocols. Similarly, Nikitenko et al. (2024) focused on a robotic walking module that controlled powered roof struts with a remote controller so that roof collapses near the mining face were prevented. Then they calculated critical load dynamics using numerical simulations, which guided the walk module to improve structure under different conditions. Or to take another method, Sui et al. (2024) used artificial neural networks to create new coal and rock recognition systems for shearers with 97.16% classification accuracy for coal seams and rocks. Such studies improved operating efficiency by coordinating shearer responses to geology for improved mining safety. Lastly, Ellem (2024) looked at the larger effects of automation on labor relations in the Queensland coal industry. Employer-driven innovations, such as automation, restructured labor relations, and bargaining processes, the paper emphasized.

7 CONCLUSION

Incorporating robots into underground coal mining will help make this process safer and more efficient for all concerned. Human workers are less exposed to dangerous conditions when robotic machines operate, and the risk of accidents and diseases is reduced compared with the old methods of mining. Robotic complexes that can be remotely controlled are able to operate from above, vital in highly dangerous situations. In particular, robotics technologies have improved productivity. Researchers have found that open-pit mining is more efficient than underground mining, and future technological innovations like 'Smart Mine’ projects should be even more effective. One must monitor robotic systems once they are installed. That includes gathering metrics on efficiency and incidents in terms of safety so that one can make adjustments and improvements to the systems. The study underscores the necessity to integrate novel technologies (like neural networks for machine control and telemetry-driven automated systems) for autonomous operations. They're critical for making machine systems more user-friendly and human assisted. The report calls for conformance to safety guidelines issued by bodies such as NIOSH and MSHA. Using robotics in mining is compliant with safety protocols, which will lead to safer operations, thanks to such rules. The bottom line: robotics and automation of the underground coal mine can significantly increase not only the efficiency but also the level of safety to enable a more sustainable and safer future for mining.

8 CHALLENGES AND FUTURE SCOPE IN ROBOTICS FOR UNDERGROUND COAL MINING

Robotics are emerging for the future in the underground coal mining industry, which has many challenges. Here are the key points:

8.1 Challenges

- High Implementation Costs: Robotics systems can cost a lot in the beginning. This includes purchasing technology, hiring, and maintaining employees, and could prevent companies from adopting these technologies.
- Employee Resistance: Employees have often resisted the automation shift. Workplace loss and training can prevent mining robotics deployment.
- Environmental Adaptability: Robots need to be capable of working well under the harsh environments of mines in the depths of the ground with their dim light and irregular surfaces. Existing technologies cannot respond optimally to these environmental challenges.
- Safety Regulations Compliance: Compliance with rigorous safety rules provided by government agencies such as MSHA can make robotic installations a challenging process. The safety of such technologies is essential to their adoption and success.
- Technological Limitations: Current robotic technologies might not be up to the task of precise navigation and processing real-time data in deep subsurface environments. These constraints will require constant improvements in sensor technology and algorithms.

8.2 Future Scope

- Advancements in AI and Machine Learning: AI and machine learning are the future of mining robotics. Such technologies can aid in decision-making, navigation, and machine predictive maintenance.

- Collaborative Robotics: Collaborative robots (cobots) that can cooperate with human miners are a bright prospect. These can help with dangerous work while keeping humans safe and increasing overall efficiency.
- Teleoperation and Remote Monitoring: The next generation might focus on increasing teleoperation to enable remote controllers for robotics. This can greatly increase safety and operational efficiency in dangerous mining environments.
- Integration of IoT and Data Analytics: With the help of IoT technologies, you can use data in real time for collection and analysis, making it easier to make the right decision and operational insights. This integration can improve security and mining efficiency.
- Sustainability Practices: With the advancement of the sector in green technologies, robotics can help mitigate the impact on the environment. Coal mining in the future will need to find innovative solutions to reduce pollution and better manage resources.

REFERENCES

ABOELEZZ, A. et al. (2023). Intrinsically Safe Drone Propulsion System for Underground Coal Mining Applications: Computational and Experimental Studies. Drones, 7(1), pp. 1–23. https://doi.org/10.3390/drones7010044

ALLAWADHI, P. (2024). Robotics: who are the leaders in robotic mining for the mining industry? [Online] Mining Technology. Available from: https://www.mining-technology.com/data-insights/innovators-robotics-robotic-mining-mining/ [Accessed 3/11/2024]

ANSI. (2012). ANSI/RIA R15.06-2012, Industrial Robots and Robot Systems - Safety Requirements (CONTAINS CORRIGENDUM). [Online] ANSI Webstore. Available from:https://webstore.ansi.org/standards/ria/ansiriar15062012?srsltid=AfmBOorzIKaGaDemAAXaDKNbsAu0vaJO1wv6_mkm5L6QziObmm6N09Jf [Accessed 5/11/2024]

ARDILA, J. P. C. et al. (2023). Arguing Operational Safety for Mixed Traffic in Underground Mining. 2023 18th Annual System of Systems Engineering Conference (SoSe), pp. 1–7. https://doi.org/10.1109/sose59841.2023.10178525

AYEISHA, B. AND ANGGORO, Y. (2024). Driving Towards Digitalization and Industry 4.0 in the Coal Mining Sector. Jurnal Ilmiah Manajemen Dan Bisnis, 10(1), pp. 38–52. https://doi.org/10.22441/jimb.v10i1.24864

CASTELLANOS-ARDILA, J. P., HANSSON, H. AND PUNEKKAT, S. (2022). Safe Integration of Autonomous Machines in Underground Mining Environments. 2022 IEEE

International Symposium on Systems Engineering (ISSE), pp. 1–8. https://doi.org/10.1109/isse54508.2022.10005369

Centers for Disease Control and Prevention (CDC). (2023). Robotics and Intelligent Mining Technology and Workplace Safety Research (CDC). Federal Grants & Contracts, 47(8), p. 7. https://doi.org/10.1002/fgc.32931

CHAKRAVORTY, A. (2019). Underground Robots: How Robotics Is Changing the Mining Industry. Eos, 100. https://doi.org/10.1029/2019eo121687

CHENG, Z. et al. (2023). A novel vision-guided strategy for accurately delivering the drill pipe of the horizontal directional drilling rigs. 2022 Workshop on Electronics Communication Engineering (WECE 2022), 2022, Xi'an, China, 12720, pp. 143–148. https://doi.org/10.1117/12.2675037

CHENGLIN, H. (2023). Structure Design and Simulation of Robot Arm for Confined Space Inner Roadway Repair. 2023 IEEE 3rd International Conference on Power, Electronics and Computer Applications (ICPECA), pp. 441–444. https://doi.org/10.1109/icpeca56706.2023.10075861

DABEK, P. et al. (2022). An Automatic Procedure for Overheated Idler Detection in Belt Conveyors Using Fusion of Infrared and RGB Images Acquired during UGV Robot Inspection. Energies, 15(2), pp. 1–20. https://doi.org/10.3390/en15020601

DU, Y. et al. (2023). Applications of Machine Vision in Coal Mine Fully Mechanized Tunneling Faces: A Review. IEEE Access, 11, pp. 102871–102898. https://doi.org/10.1109/access.2023.3317048

DUDDU, P. (2024). Robotics: who are the leaders in robotic coal mining? [Online] Mining Technology. Available from: https://www.mining-technology.com/data-insights/robotics-innovation-leading-companies-in-robotic-coal-mining/ [Accessed 3/11/2024]

ELLEM, B. (2024). Industrial relations as power, place and time: the case of Queensland coal mining. Labour & Industry a Journal of the Social and Economic Relations of Work, pp. 1–19. https://doi.org/10.1080/10301763.2024.2357739

EVGENY, K. AND ANATOL'EVNA, K. I. (2020). Factor Model of Labor Productivity in the Coal Industry. Bulletin of Kemerovo State University Series Political Sociological and Economic Sciences, 5(4), pp. 557–567. https://doi.org/10.21603/2500-3372-2020-5-4-557-567

FAN, C. (2024). Key technologies for intelligent mining of difficult-to-mine coal seams. Journal of Civil Engineering and Urban Planning, 6(1), pp. 69–75. https://doi.org/10.23977/jceup.2024.060110

GAOKGORWE, T. (2023). The Application of Robotics in Deep Level Mining in South Africa and its Influence on Health and Safety. Dissertation (Master's), University of the Witwatersrand. https://hdl.handle.net/10539/38954

GUO, A., WANG, B. AND ZHAO, M. (2022). Design and Application of Control System for Underground Inspection Robot. 2022 7th Asia-Pacific Conference on Intelligent Robot Systems (ACIRS), pp. 18–21. https://doi.org/10.1109/acirs55390.2022.9845646

GUO, W. (2023). Design and Experiment of Intelligent Cover Robot for Coal Mining. In Lecture notes in mechanical engineering (pp. 759–770). https://doi.org/10.1007/978-981-19-9398-5_45

HARGRAVE, C. O., JAMES, C. A. AND RALSTON, J. C. (2017). Infrastructure-based localisation of automated coal mining equipment. International Journal of Coal Science & Technology, 4(3), pp. 252–261. https://doi.org/10.1007/s40789-017-0180-3

HE, S. et al. (2023). Advances in mining safety theory, technology, and equipment. ADVANCES IN GEO-ENERGY RESEARCH, 10(2), pp. 71–76. https://doi.org/10.46690/ager.2023.11.01

INOZEMTSEV, M., NIKITINA, S. AND KONONOV, M. (2018). Monitoring the Displacement the Roof of Underground Mines for Safety of Mining Operations. E3S Web of Conferences, 41, pp. 1–5. https://doi.org/10.1051/e3sconf/20184101021

ISO. (2011a). Robots and robotic devices — Safety requirements for industrial robots, Part 1: Robots. [Online] ISO 10218-1:2011. Available from: https://www.iso.org/standard/51330.html [Accessed 5/11/2024]

ISO. (2011b). Robots and robotic devices — Safety requirements for industrial robots, Part 2: Robot systems and integration. [Online] ISO 10218-2:2011. Available from: https://www.iso.org/standard/41571.html [Accessed 5/11/2024]

ISO. (2019). Earth-moving machinery and mining — Autonomous and semi-autonomous machine system safety. [Online] ISO 17757:2019. Available from: https://www.iso.org/standard/76126.html [Accessed 5/11/2024]

JALAS, P. et al. (2018). Information Modeling of an Underground Laboratory for the R&D of Mining Automation and Tunnel Construction Robotics. 2018 Proceedings of the 35th ISARC, pp. 806–810. https://doi.org/10.22260/isarc2018/0112

JÄMSÄ-JOUNELA, S. L. and BAIDEN, G. (2023). Automation and Robotics in Mining and Mineral Processing. In Springer handbooks (pp. 909–921). https://doi.org/10.1007/978-3-030-96729-1_41

JONES, E. et al. (2019). Advances and applications for automated drones in underground mining operations. Deep Mining 2019: Proceedings of the Ninth International

Conference on Deep and High Stress Mining, pp. 323–334. https://doi.org/10.36487/acg_rep/1952_24_jones

KHARLAMPENKOV, E. et al. (2020). Factor Model of Labour Productivity in the Coal Mining Industry. E3S Web of Conferences, 174, pp. 1–12. https://doi.org/10.1051/e3sconf/202017401033

KLIMOV, V. V. (2019). Geomechanical feasibility of underground coal mining technology using control systems of electro-hydraulic shield supports for longwall mining. IOP Conference Series: Materials Science and Engineering, 560, pp. 1–5. https://doi.org/10.1088/1757-899x/560/1/012067

KOLAPO, P. (2024). THE METHODOLOGY FOR INTEGRATING ROBOTIC SYSTEMS IN UNDEGROUND MINING MACHINES UNDEGROUND MINING MACHINES. Dissertation (PhD), University of Kentucky. https://doi.org/10.13023/etd.2024.06

KOLAPO, P. et al. (2024). Integrating robotic systems in underground roof support machine. Journal of Industrial Safety, 1(1), pp. 1–9. https://doi.org/10.1016/j.jinse.2024.100002

KOVAL, A., MANSOURI, S. S. and KANELLAKIS, C. (2023). Machine learning for ARWs. In Elsevier eBooks (pp. 159–174). https://doi.org/10.1016/b978-0-12-814909-6.00016-0

KUMAR, R., KUMAR, P. and DAS, D. G. (2022). IoT Based Coal Mine Safety Monitoring and Alerting System. 2022 4th International Conference on Advances in Computing, Communication Control and Networking (ICAC3N), pp. 1729–1731. https://doi.org/10.1109/icac3n56670.2022.10074169

LECLERC, M. A. et al. (2023). NetherDrone: a tethered and ducted propulsion multirotor drone for complex underground mining stope inspections. Drone Systems and Applications, 11, pp. 1–17. https://doi.org/10.1139/dsa-2023-0001

LEDANGE, S. M. and MATHURKAR, S. S. (2016). Robot based Wireless Monitoring and Safety System for Underground Coal Mines using ZigBee. International Journal of Electronics and Communication Engineering, 3(10), pp. 29–32. https://doi.org/10.14445/23488549/ijece-v3i10p106

LI, Y. et al. (2019). Development and applications of rescue robots for explosion accidents in coal mines. Journal of Field Robotics, 37(3), pp. 466–489. https://doi.org/10.1002/rob.21920

LIEN, L. (2013). Advances in coal mining technology. In Elsevier eBooks (pp. 193–225). https://doi.org/10.1533/9780857097309.2.193

MA, L. and CHEN, Q. (2021). Problems and Research on Underground Charging Safety of Power Battery for Coal Mine Robot. IOP Conference Series: Earth and Environmental Science, 651, pp. 1–5. https://doi.org/10.1088/1755-1315/651/3/032100

MANSOURI, S. S. et al. (2020). MAV Navigation in Unknown Dark Underground Mines Using Deep Learning. 2020 European Control Conference (ECC), pp. 1943–1948. https://doi.org/10.23919/ecc51009.2020.9143842

MARATHE, A. et al. (2024). Coal Mining Surveillance Robot. 2024 3rd International Conference on Applied Artificial Intelligence and Computing (ICAAIC), pp. 1940–1944. https://doi.org/10.1109/icaaic60222.2024.10575836

MARSHALL, J. A. et al. (2016). Robotics in Mining. In Springer handbooks (pp. 1549–1576). https://doi.org/10.1007/978-3-319-32552-1_59

MATLOOB, S., Li, Y. and KHAN, K. Z. (2021). Safety Measurements and Risk Assessment of Coal Mining Industry Using Artificial Intelligence and Machine Learning. Open Journal of Business and Management, 09(03), pp. 1198–1209. https://doi.org/10.4236/ojbm.2021.93064

MENENDEZ, E. et al. (2019). uSLAM Implementation for Autonomous Underground Robot. 2019 IEEE SmartWorld, Ubiquitous Intelligence & Computing, Advanced & Trusted Computing, Scalable Computing & Communications, Cloud & Big Data Computing, Internet of People and Smart City Innovation (SmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI), pp. 237–241. https://doi.org/10.1109/smartworld-uic-atc-scalcom-iop-sci.2019.00083

MESHCHERYAKOV, Y. and MESHCHERYAKOV, R. (2018). Automated system of monitoring and positioning of functional units of mining technological machines for coal-mining enterprises. MATEC Web of Conferences, 161, pp. 1–6. https://doi.org/10.1051/matecconf/201816103017

MIN, F., ZHAI, Z. and JIN, C. (2022). Research on a hydraulic manipulator arm of an automatic bottom laying robot for underground roadway in coal mine. ITM Web of Conferences, 47, pp. 1–7. https://doi.org/10.1051/itmconf/20224701030

Mine Safety and Health Administration. (2015). Proximity Detection Systems for Continuous Mining Machines in Underground Coal Mines. [Online] Federal Register. Available from: https://www.federalregister.gov/documents/2015/01/15/2015-00319/proximity-detection-systems-for-continuous-mining-machines-in-underground-coal-mines [Accessed 5/11/2024]

MOUSAVI, M., SHEN, X. and LI, B. (2023). Online Safety Risk Management for Underground Mining and Construction Based on IoT and Bayesian Networks. 2023 Proceedings of the 40th ISARC, pp. 498–505. https://doi.org/10.22260/isarc2023/0067

MSHA Safety Services. (2023). MSHA Part 46 VS Part 48: What is the Difference?. [Online] Mine Safety Trainings. Available from: https://mshasafetyservices.com/part-46-part-48-which-training-do-i-need/ [Accessed 5/11/2024]

NANADREKAR, J. S. J. et al. (2022). Robots in Mining. In Lecture notes in civil engineering (Vol. 228, pp. 625–631). https://doi.org/10.1007/978-981-16-9770-8_41

NIKITENKO, M. S. et al. (2017). Robotic complex for the development of thick steeply-inclined coal seams and ore deposits. IOP Conference Series: Earth and Environmental Science, 84, pp. 1–7. https://doi.org/10.1088/1755-1315/84/1/012002

NIKITENKO, S. et al. (2024). Robotic walking module as underground mining safety device. E3S Web of Conferences, 498, pp. 1–8. https://doi.org/10.1051/e3sconf/202449803014

NIOSH. (2019). NIOSH Seeks Data on Automation Used in Mining. [Online] Occupational Health & Safety. Available from: https://ohsonline.com/Articles/2019/03/19/NIOSH-Seeks-Data-on-Automation-Used-in-Mining.aspx?admgarea=news [Accessed 5/11/2024]

Occupational Safety and Health Administration (OSHA). (n.d.). Robotics. [Online] Safety and Health Topics. Available from: https://www.osha.gov/robotics/standards [Accessed 5/11/2024]

PAREDES, D. and FLEMING-MUÑOZ, D. (2021). Automation and robotics in mining: Jobs, income and inequality implications. The Extractive Industries and Society, 8(1), pp. 189–193. https://doi.org/10.1016/j.exis.2021.01.004

PRASHANTH, M. and LELINADEVI, A. (2015). Wireless robot for coal mines based on mixed signal processor (MSP430). International Journal of Advanced Information and Communication Technology (IJAICT), 1(12), pp. 950–954.https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=1952d4e4875049b299e6150af5cf4861b10a3cc8

PROTSENKO, A. and IVANOV, V. (2020). Comparative analysis of rrt-based methods for pathfinding in underground environment. Advanced Information Systems, 4(3), pp. 109–112. https://doi.org/10.20998/2522-9052.2020.3.15

RAJVANSHI, A. et al. (2022). Autonomous Docking Using Learning-Based Scene Segmentation in Underground Mine Environments. 2022 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR), pp. 327–334. https://doi.org/10.1109/ssrr56537.2022.10018611

RATHORE, N. S. and SRIVASTAV, A. K. (2018). A review on working condtions in indian mining industry and necessary changes for its improvement. International Journal of Marketing and Management Research (IJMMR), 9(1), pp. 1–9. https://skirec.org/wp-content/uploads/2018/03/IJMMR1Jan18-1.pdf

REN, B. et al. (2023). Research on an Intelligent Mining Complete System of a Fully Mechanized Mining Face in Thin Coal Seam. Sensors, 23(22), pp. 1–14. https://doi.org/10.3390/s23229034

RUIZ-DEL-SOLAR, J. et al. (2017). Robotics research in Chile: Addressing the needs of the local mining industry at the Advanced Mining Technology Center. International Journal of Advanced Robotic Systems, 14(1), pp. 1–10. https://doi.org/10.1177/1729881416682695

SAKTHI, S., NIRESH, J. and NEELAKRISHNAN, S. (2019). Adaptive Admittance Control for Autonomous Loading of Load Haul Dumper in Underground Coal Mining. ICMRE'19: Proceedings of the 5th International Conference on Mechatronics and Robotics Engineering, pp. 73–77. https://doi.org/10.1145/3314493.3314509

SANDVIK AB. (2024a). Automation. [Online] Sandvik Mining and Rock Technology. Available from: https://www.rocktechnology.sandvik/en/digital-solutions/automation/ [Accessed 3/11/2024]

SANDVIK AB. (2024b). Sandvik to acquire Universal Field Robots. [Online] Sandvik Group. Available from: https://www.home.sandvik/en/news-and-media/news/2024/08/sandvik-to-acquire-universal-field-robots/ [Accessed 3/11/2024]

SHAFFER, G. and STENTZ, A. (1992). A robotic system for underground coal mining. Proceedings 1992 IEEE International Conference on Robotics and Automation, 1, pp. 633–638. https://doi.org/10.1109/robot.1992.220221

SPEARING, A. J. S., ZHANG, J. and MA, L. (2021). A new automated, safe, environmentally sustainable, and high extraction soft-rock underground mining method. Journal of the Southern African Institute of Mining and Metallurgy, 121(2), pp. 89–96. https://doi.org/10.17159/2411-9717/1370/2021

STUTT, A. (2024). Sandvik expands automation reach with Universal Field Robots merger. [Online] MINING.COM. Available from: https://www.mining.com/sandvik-expands-automation-reach-with-universal-field-robots-merger/ [Accessed 3/11/2024]

SU, Y. et al. (2021). Design of the Autonomous Path Planning System for Mining Robots Based on Stereo Vision. In Lecture notes in computer science (Vol. 13016, pp. 596–605). https://doi.org/10.1007/978-3-030-89092-6_54

SUI, Y. et al. (2024). Research on Coal and Rock Recognition in Coal Mining Based on Artificial Neural Network Models. Applied Sciences, 14(2), pp. 1–17. https://doi.org/10.3390/app14020864

T.E., ERMEKOV, T.K., ISSABEK and R.K., KAMAROV. (2018). Development of underground technology for the production of coal-based plasts with complex conditions of zanging. Development of scientific foundations of resource-saving technologies of mineral mining and processing, pp. 52–82. http://lib.ktu.edu.ua/wp-content/uploads/2019/10/monograf-2_.pdf

TAUGER, V. et al. (2020). Remote-controlled robotic complex for underground mining. E3S Web of Conferences, 177, pp. 1–6. https://doi.org/10.1051/e3sconf/202017703006

THIVYABRABHA, K. et al. (2022). IoT based Automated Coal Mine Detection and Immediate Rescue Robot. 2022 International Conference on Automation, Computing and Renewable Systems (ICACRS), pp. 1338–1343. https://doi.org/10.1109/icacrs55517.2022.10029244

TISHCHENKO, I. V. and VANAG, Y. V. (2022). Automation and robotization of solid mineral mining. Interexpo GEO-Siberia, 2(3), pp. 325–333. https://doi.org/10.33764/2618-981x-2022-2-3-325-333

TREVELYAN, J., HAMEL, W. R. and KANG, S. C. (2016). Robotics in Hazardous Applications. In Springer handbooks (pp. 1521–1548). https://doi.org/10.1007/978-3-319-32552-1_58

TRYBAŁA, P. et al. (2022). Calibration of a multi-sensor wheeled robot for the 3d mapping of underground mining tunnels. the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences/International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVIII-2/W2-2022, pp. 135–142. https://doi.org/10.5194/isprs-archives-xlviii-2-w2-2022-135-2022

VALUEV, A. M. and VOLKOVA, L. P. (2020). Problems of Intelligent Automation of Unmanned Underground Coal Mining. In Advances in intelligent systems and computing (Vol. 902, pp. 507–516). https://doi.org/10.1007/978-3-030-12082-5_46

VALVERDE, M. (2024). Komatsu Displays Underground Coal Mining Technology at MINExpo. [Online] Coal Age. Available from: https://www.coalage.com/departments/breaking-news/komatsu-displays-underground-coal-mining-technology-at-minexpo/ [Accessed 3/11/2024].

WANG, W. et al. (2014). Development of search-and-rescue robots for underground coal mine applications. Journal of Field Robotics, 31(3), pp. 386–407. https://doi.org/10.1002/rob.21501

WANG, X. et al. (2022). A Cooperative Control Method for Excavation Support Robot with Desired Position/Posture. Applied Sciences, 12(18), pp. 1–22. https://doi.org/10.3390/app12189262

WELSH, J. H. (1989). Automation and robotics technology for intelligent mining systems. [Online] NASA Technical Reports Server (NTRS). Available from: https://ntrs.nasa.gov/citations/19900019702 [Accessed 3/11/2024].

WOOLMER, D. et al. (2020). Use of Drone based Lidar technology at Olympic Dam Mine and initial Technical Applications. MassMin 2020: Proceedings of the Eighth International Conference & Exhibition on Mass Mining, pp. 565–582. https://doi.org/10.36487/acg_repo/2063_38

WORMALD, R. (2014). Invited Speakers. Clinical & Experimental Ophthalmology, 42(S1), pp. 1-7. https://doi.org/10.1111/ceo.12445

XUE, G. et al. (2022). Research on Underground Coal Mine Map Construction Method Based on LeGO-LOAM Improved Algorithm. Energies, 15(17), pp. 1–17. https://doi.org/10.3390/en15176256

XUSHENG, X. et al. (2018a). Analysis of Wireless Electromagnetic Wave Propagation Mechanism for Coal Mine Rescue Robot. 2018 IEEE International Conference on Real-time Computing and Robotics (RCAR), pp. 64–67. https://doi.org/10.1109/rcar.2018.8621677

XUSHENG, X. et al. (2018b). Analysis of Wireless Electromagnetic Wave Propagation Mechanism for Coal Mine Rescue Robot. 2018 IEEE International Conference on Real-time Computing and Robotics (RCAR), Kandima, Maldives, pp. 64–67. https://doi.org/10.1109/rcar.2018.8621677

YANG, W. et al. (2019). Infrared LEDs-Based Pose Estimation with Underground Camera Model for Boom-Type Roadheader in Coal Mining. IEEE Access, 7, pp. 33698–33712. https://doi.org/10.1109/access.2019.2904097

ZHENG, J. et al. (2021). A LiDAR-Aided Inertial Positioning Approach for a Longwall Shearer in Underground Coal Mining. Mathematical Problems in Engineering, 2021(1), pp. 1–15. https://doi.org/10.1155/2021/6616090

ZHU, D. et al. (2022). A Coupled Visual and Inertial Measurement Units Method for Locating and Mapping in Coal Mine Tunnel. Sensors, 22(19), pp. 1–18. https://doi.org/10.3390/s22197437

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MACHINE LEARNING METHODS OF SATELLITE IMAGE ANALYSIS FOR MAPPING GEOLOGIC LANDFORMS IN NIGER: A COMPARISON OF THE AÏR MOUNTAINS, NIGER RIVER BASIN AND DJADO PLATEAU

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Abstract: This study analyses geological landforms and land cover types of Niger using spaceborne data. A landlocked African country rich in geological structures, Niger is notable for contrasting environmental regions which were examined and compared: 1) lowlands (Niger River basin); 2) Aïr Mountains; and 3) Djado Plateau. The methodology is based on machine learning (ML) models and programming applied for Earth observation data. Spatio-temporal analysis was performed using Landsat 8-9 OLI-TIRS multispectral images classified by GRASS GIS. Data were processed by scripts using ML algorithms by modules r.random, r.learn.train, r.learn.predict, i.cluster, and i.maxlik. The algorithms of probabilistic forecasting included support vector machine (SVM), random forest (RF), decision tree classifier and K neighbors classifier. Variations in landscapes caused by water deficit and soil erosion were analyzed, and parallels between geologic and environmental setting were drawn. The intra-landscape variability of patches within Niger is revealed from 2014 to 2024. Landscape patterns are affected by drought periods in central Niger, geological setting of mountains, distribution of crust karst pits and sinkholes in eastern Niger. Western region of the Niger River basin shown land cover patterns linked to hydrological effects of soil erosion. This paper shows the use of ML methods for geological-environmental analysis.

Keywords: machine learning, geology, satellite image, remote sensing, cartography

1 INTRODUCTION

Geological-environmental monitoring is critical for dry arid regions of Sahara-Sahelian Africa. In this region, the variability of landforms, extent of land cover types and the

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complexity of landscape structure are entirely controlled by the rhythm of regional precipitation and climate effects (Gond et al. 2004; Lemenkova 2023a, 2023b). At the same time, in contrast to other African countries, the variability of diverse landscapes of Niger is not well documented. Environmental and geological analysis is also important for modelling groundwater distribution and subsurface resources, which provides socio-economic support of population. Niger, one of the poorest countries in the world, has limited access to safe drinking potable water, especially for rural population (Lasagna et al. 2015). Hence, geological and environmental mapping of its various landscapes using satellite images processed by advanced cartographic tools contributes to monitoring natural resources of Niger. This research presents comparative environmental analysis of Niger. The data were mapped using machine learning (ML) methods of GRASS GIS by cartographic scripts.

2 STUDY AREA

The study area is focused on Niger, a landlocked country in West Africa, Figure 1. Specifically, three contrasting landscape regions of Niger related to diverse watersheds were compared and examined: 1) lowlands (Niger River basin), 2) mountainous area (Aïr Mountains) and 3) plateau (Djado Plateau). The location of Niger is restricted by the coordinates between 11° and 24°N, and 0° and 16°E. In this research, we focus on the three selected study areas of Niger that have contrasting geographic, environmental and geologic setting: lowlands are presented by the Niger River basin, mountainous area is exemplified by the Aïr Mountains and the plateau is studied using Djado Basin. The location of the Landsat images with these three regions on the topographic map of Niger is shown in Figure 1

Geospatial data of reliable source and appropriate resolution is critically important for mapping and environmental research of Niger, because of its complex landscape and data scarcity (Meister et al., 1994). Located between the Sahara and Sahel regions, Niger exhibits significantly variable topography, ranging from its lowest point in the Niger River (200 m heights) until Mont Idoukal-n-Taghès in the Aïr Mountains (or Massif) at 2,022 m (Ingram 1990).

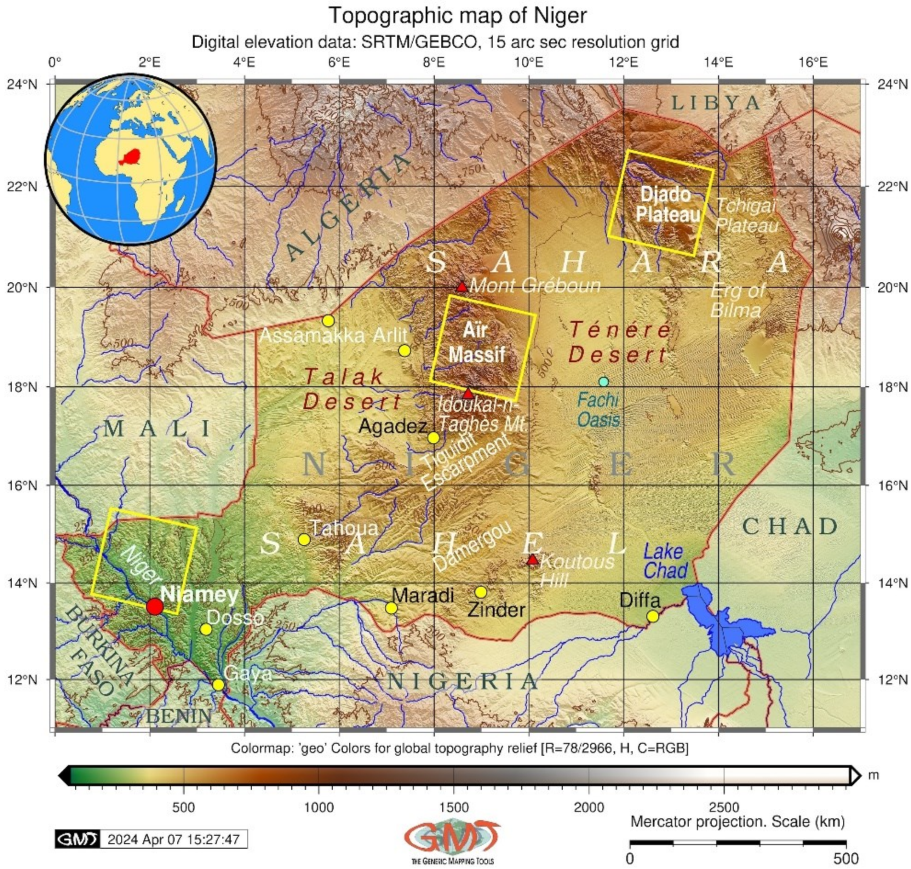

Figure 1 Three study areas on the topographic map of Niger: Niger River flow, Aïr Mountains and Djado Plateau. Data source: GEBCO. Software: GMT version 6.4.0. Map source: author

The geomorphology of Niger includes a variety of Saharo-Sahelian landforms (Keeling 2009) which reflect its complex geologic structure. Thus, Niger's terrain typically exhibits a mosaic of Lower Createaceous (KI), Quaternary (Q) and Tertiary (T) outcrops on the south, and the Precambrian (pCm) groups in the west of the country on the border with Burkina Faso (Chardon, 2023). Steep vegetation slopes of the Tiguidit Escarpment with elevation around 500 m a.s.l. are covered by Cretaceous rocks. Cretaceous assembly and fragmented of Carboniferous rocks are accumulated in the north-eastern region of the country around the Tchigaï Plateau on the border with Chad (Lemenkova, 2023c), which was formed during Paleozoic, Figure 2.

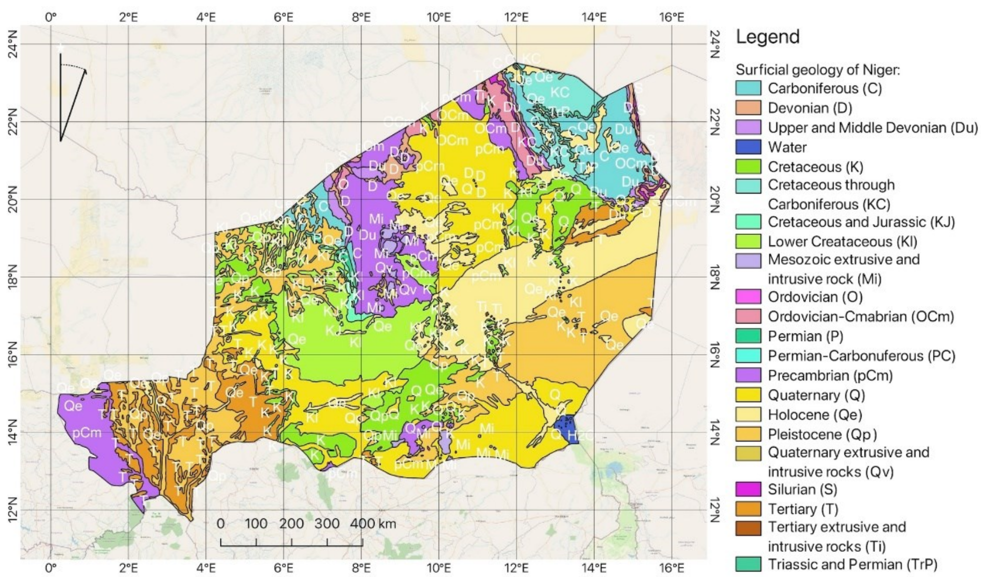

Figure 2 Surficial geology and lithologic units of Niger. Data: USGS, OpenStreetMaps (OSM). Software: QGIS. Map source: author

Western Niger has been largely occupied by the Iullemmeden sub-Saharan inland basin which experienced was subducted and inundated in Permo-Triassic period and then downwarped during the Late Cretaceous to Paleogene which reflected in its sedimentation from Cambrian to Pleistocene periods, Figure 3. Regional distribution of the sedimentary and tectonic provinces Republic of Niger can be classified into two parts (Zanguina et al. 1998): a Palaeozoic platform-type province in the north and west, and a series of Mesozoic grabens in the east that cover the Chad geological province, Figure 3.

As a landlocked country of West Africa, Niger has arid to semi-arid climate varying accordingly to the latitude and regulated by local geomorphic patterns (Favreau et al. 2009). Thus, the hotter and drier climate is notable for desert areas which lead even to fires (Diouf et al. 2012; McShane 1987), while southern region of the Niger River basin has a tropical climate (Lemenkova, Debeir, 2023). Moreover, mountain slopes attenuate temperature fluctuations and support variability of vegetation types. Soil erosion is one of the most important environmental problems in Niger, due to the deficit of water resources and increasing droughts in Sahel.

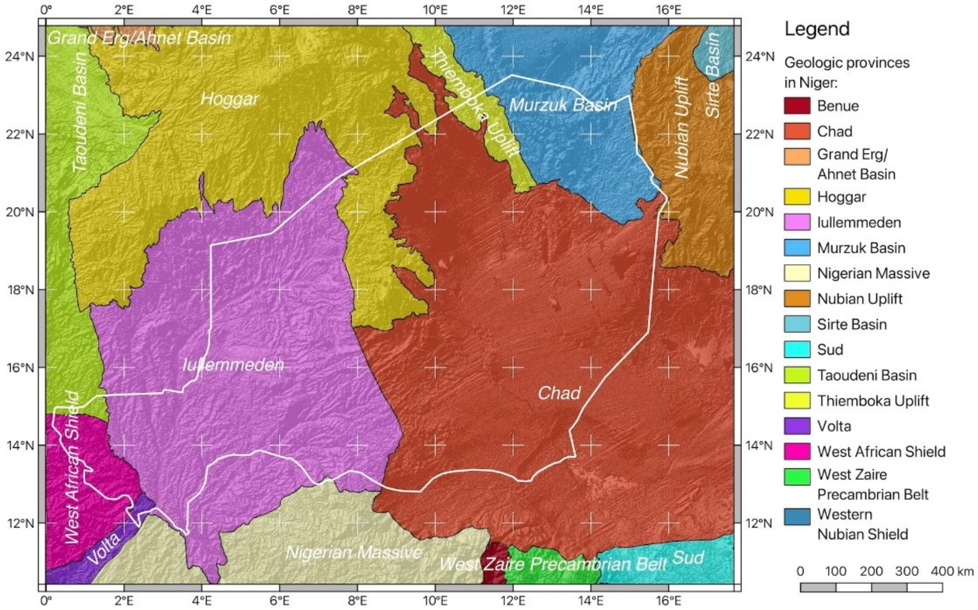

Figure 3 Geologic provinces of Niger. Data: USGS. Background hillshade relief: GEBCO. Software: QGIS. Map source: author.

The effects of the erosion, increased by drying climate, lead to land cover change through the removal of the fertile fraction of the soil which in turn affects vegetation and habitat distribution. Cumulative effects from the irregular rainfall patterns in desert areas, soil erosion and land cover changes have implications for soil and water resources, leads to land degradation and affects agriculture practices in Niger.

Geological processes in Northern Niger favored formation of valuable minerals which is currently reflected in uranium resources around (Sani et al. 2022, Mamane Mamadou et al. 2020). The Devonian and Carboniferous successions are mostly located in the Murzuq Basin and the sub-Basin of the Djado Plateau (Mergl et al 2000). The Djado Basin forms the upper part of the Cambrian – Late Ordovician series, consists of the preglacial Tigillites Sandstone Formation of former ice sheet. Its inner part now consists mostly of glaciomarine deposits that form sandstone ridges of the related series of Felar-Felar Formation (Denis et al. 2007). The petroleum potential in eastern Niger corresponds to the distribution of the complex rift system with sedimentary fill ranging in ages from Late Jurassic to Early Tertiary. Thus, the deposits in eastern Niger include such unique source rocks as organic-rich shales of Oligocene, Eocene, Paleocene, and other ages. These oil-generating samples provide the origin of the hydrocarbons (Harouna, Philp 2012).

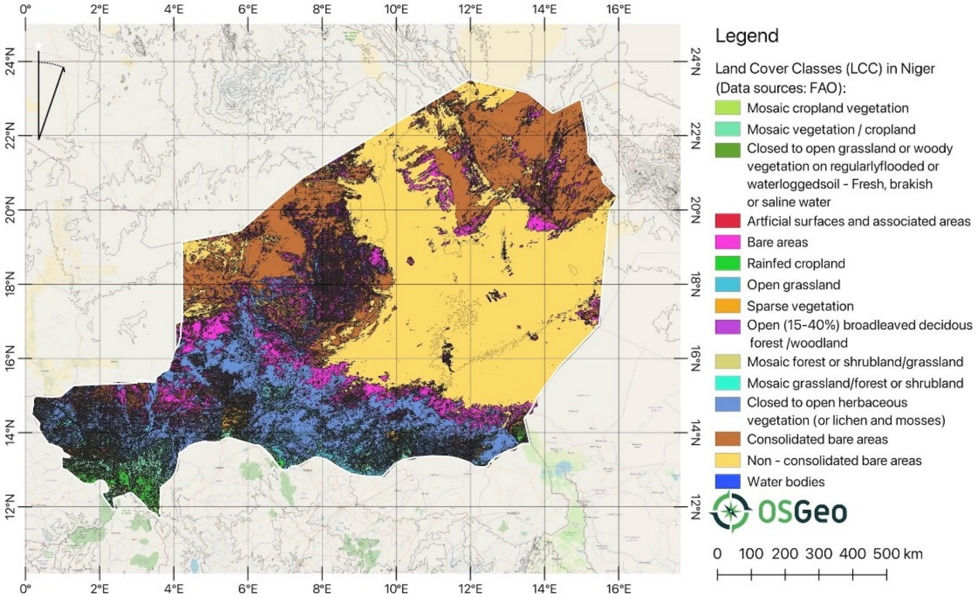

Figure 4 Land cover types in Niger. Data source: Food and Agriculture Organization (FAO). Background map: OSM. Software: QGIS. Map source: author

Geological complexity and variability of the country formed various geomorphic landforms that are reflected in rich landscapes. The predominantly desert plains and sand dunes of Niger alternate with flat to rolling terrain of savanna shapes the landscapes in the south and hills dozens of mountain peaks over 500 m in the north, Figure 1. One of the important peaks is created by the Aïr Massif which presents important environmental feature in northern Niger through regulating climate extremities of Sahara and providing surrounding ecosystems with natural resources and water. The essential hydrological mountains-lowland linkage provides freshwater for the adjacent lowlands (Viviroli et al. 2007).

As a consequence, the Aïr Massif forms an island of green Sahel climate which supports a wide variety of life which well contrasts with the surrounding desert regions of Sahara. For instance, wadis stream originating in the ranges of the Aïr massif provide a habitat for rare species that seek for water from the Saharo-Sahelian deserts (Ostrowski et al. 2001). Moreover, surface runoff from the mountain ranges accumulated in depressions contribute to the groundwater resources which are crucial in arid lands of Niger for supporting life (Molina et al. 2017; Verdin, 1996). Such oases made by ephemeral streams during pluvial periods create sources of rainwater and support life in Sahara-Sahel regions.

The terrestrial ecoregions of Niger are influenced both by climate variations of arid region and regional geologic setting and include diverse types. The essential categories comprise deserts and semi-deserts in the north, steppes, savannah and grasslands in the south (Justice, Hiernaux, 1986), and xeric woodlands in the mountain ranges, Figure 4. Such variety is explained by complex geologic structure which reflects strong relationship between the lithologic setting and land cover types in Niger. This linkage can be explained by soil variables which have a control for vegetation structure and composition. Thus, mineral content of soil is formed under the specific regional lithological setting with rock outcrops that influence local physical characteristics of soil properties (grain size, composition, content, porosity, texture, etc.). Moreover, the hydrogeologic setting and access to groundwater is related to aquifers of soil with diverse properties (Dodo, Zuppi, 1997).

Nevertheless, certain geomorphic processes negatively affect the environmental setting. For example, the Niger River is threatened with silting up due to the development of alluvial fans in south-west Niger around Niamey (Mamane Barkawi et al. 2023).

The examples of the climate effects on current landscapes can be illustrate by the paleogeographic reconstructions in Niger. For example, modern silt-rich lacustrine sediments indicate the distribution of paleolake depressions during earlier periods with high humidity (Felix-Henningsen, 2000). In contrast, during arid climatic period, these paleolakes decresed in size and are currently occupied by dunes and vast areas of sands in deserts. Thus, variations in groundwater in the northern and southern Sahara are related to the climatic oscillations since Holocene which also affected the organic matter content from surface vegetation and level of water infiltration through soil (Dodo, Zuppi, 1999). The remnants of such palaeosoils and aeolian deposits fill karsts and sinkholes in eastern Niger (Sponholz, 1994).

3 DATA

Satellite images provide a precious source of information for environmental mapping which is proved by their use in numerous related studies (Mering et al. 2010, Lemenkova 2023d, Wylie et al. 1992). For instance, remote sensing data can be used to identify the expanding settlements and detecting built-up areas (Tiepolo, Galligari, 2022), for mapping soil in desert regions (Mulders, Girard, 1993) or climate modelling (Dione et al. 2014, Emetere, Akinyemi, 2017). Therefore, in this study, we used the Landsat satellite images which were selected as data source because of their open availability, high quality and reputation in geospatial research.

The original raw data covering three study areas are presented as a series of images in natural colors, Figure 5. The data were downloaded from the open repository EarthExplorer (https://earthexplorer.usgs.gov/) by United States Geological Survey (USGS). The dataset of Landsat 8-9 OLI/TIRS includes six images covering three selected study areas.

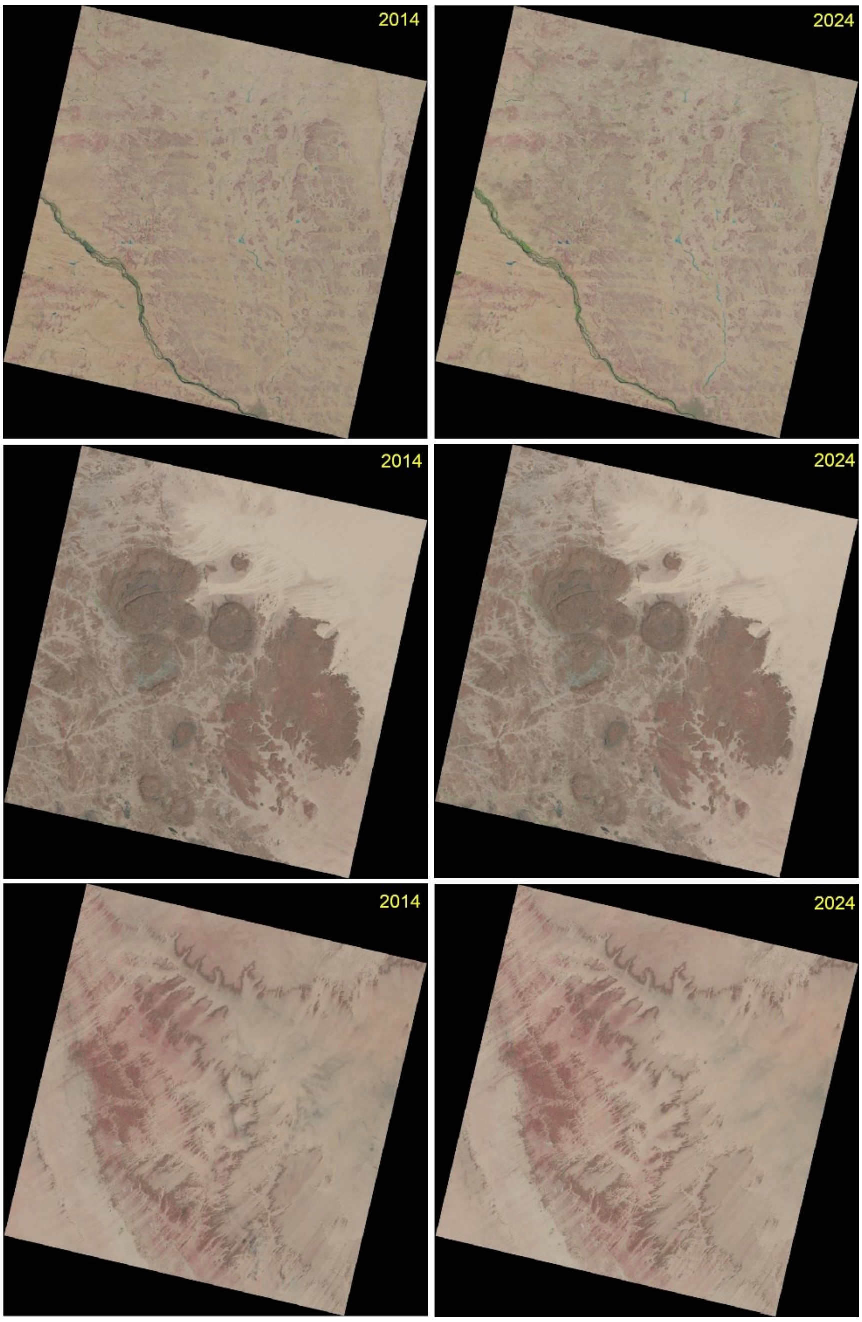

Figure 5 Original data: Landsat 8-9 OLI/TIRS images on three regions of Niger, collected during the spring period (April) on years with ten gap interval on 2014 and 2024. Data source: USGS. Compilation source: author

The selection of these data is explained by well characterization of the diversity of landform types and land cover structure in Niger: 1) lowlands (Niger River basin), 2) mountainous area (Aïr Mountains) and 3) plateau (Djado Plateau). The images were taken on two years: 2014 and 2024 for each scene where the image for 2014 was used as training dataset for supervised machine learning techniques providing seed for classification. The data were selected on March in all cases to cope with climate effects. Thus, the climate area in southern Niger is tropical where wet periods with abundant precipitation and rainfalls lasts normally from June to September, followed by a long dry season October–May (Oguntunde et al. 2014). As a consequence, the quality of satellite images might be affected by haze and higher moisture during this period. Therefore, the images were taken on March for years 2014 and 2024 for all the scenes.

4 METHODS

The methodology is based on the cartographic program GRASS GIS with its modules for machine learning. Specifically, the following four ML algorithms were used for image classification for scenes on 2024: 1) Random Forest Classifier, 2) Decision Tree Classifier, 3) K Neighbors Classifier, and 4) Support Vector Machine Classifier (SVMC). Additionally, clustering using k-means algorithms was performed for images in 2014. These data served as training pixels for ML approach. The high-resolution regional topography of Niger is mapped using GEBCO grid processed using Generic Mapping Tools (GMT) using scripts, as explained in earlier works (Lemenkova, 2022a, 2022b).

Scripting approach to cartographic data processing using several modules of GRASS GIS were performed for six Landsat satellite images by using a combination of the following methodological steps in a single process stepwise.

1. Firstly, the data were imported with the image subset containing 7 Landsat multispectral bands using 'r.import' module: “r.import input=/Users/path/LC08<file_name>B1.TIF output=L_2014_01 extent=region resolution=region”. In the same way, the GEBCO grid was imported for relief background.

2. Secondly, the computational region was defined to match the scene using 'g.region' of GRASS GIS as follows: g.region raster=L_2014_01 -p. This command enabled to clip the necessary part of the region limited to the coordinates of the study areas from the GEBCO map which covers global extent.

3. Thirdly, the assignment of pixels to clusters, fractured surface and diverse land cover types are made by 'i.cluster' module which generates signature file and reports using k-means clustering algorithm. Snippet of the code is as follows: "i.cluster group=L_2014 subgroup=res_30m signaturefile=cluster_L_2014 classes=10 reportfile=rep_clust_L_2014.txt".

4. The unsupervised classification was performed by 'i.maxlik' module using the following code: i.maxlik group=L_2014 subgroup=res_30m signaturefile=cluster_L_2014 output=L_2014_clusters reject=L_2014_cluster_reject. This step includes the unsupervised classification which uses signature obtained in previous step of clustering. The results of the maximum likelihood discriminant analysis classifier are then used as training data for the next step of ML that requires training dataset from previous classification.

5. Generating training polygons was performed using clustering technique by k-means and maximum likelihood discriminant analysis classifier. The data were quantified to detect landform shapes and contours of land cover categories.

6. Examining the obtained product for accuracy was performed using rejection probability function that evaluates the correctness of the assigned pixels using chi-square test. The data are then visualised using a combination of commands as follows: d.rast L_2014_cluster_reject d.legend raster=L_2014_cluster_reject title="2014" title_fontsize=19 font="Helvetica" fontsize=17 bgcolor=white border_color=white.

The next step includes the Machine Learning (ML) method of image classification which included four different algorithms. In general, ML can be defined as a system that models the brain working principle of human beings. ML is comprised of training data that includes the pixels obtained in the previous classifications (in this case, data for 2014).

1. The fist algorithm included the Random Forest Classifier. The process included grouping data by ‘i.group’ which combines the multispectral bands into one group as follows: i.group group=L_2024 subgroup=res_30m input=L_2024_01<...>L_2024_07 –overwrite. Afterwards, the model is trained using ‘r.learn.train’ function as follows: “r.learn.train group=L_2024 training_map=training_pixels model_name=RandomForestClassifier n_estimators=500 save_model=rfc_model.gz.

2. The ML supervised learning algorithm is developed for training machine to classify images which iteratively adapts the pixels into the best suitable class according to its spectral reflectance value. To this end, the prediction of this assignment is performed using the r.learn.predict module as follows: “r.learn.predict group=L_2024 load_model=rfc_model.gz output=rfc_classification_2024”.

3. Afterwards, raster categories are automatically applied to the classification output using ‘r.category’ module as follows: “r.category rfc_classification_2024”. The maps are then displayed using the combination of modules ‘d.rast’ for the images, ‘d.vect’ for isolines derived from GEBCO grid and d.legend for adding the legend on the maps.

The same methodological scheme was applied to the algorithms Decision Tree Classifier, K Neighbors Classifier and Support Vector Machine Classifier (SVM). In those cases, the name of the algorithm is explicitly added in the function of training module “model_name”, e.g. for KNeighborsClassifier it is as follows: "r.learn.train group=L_2024 training_map=training_pixels model_name=KNeighborsClassifier n_estimators=500 save_model=knc_model.gz". The same approach was applied to the algorithms of Decision Tree Classifier and SVM, accordingly.

During the last decades, automation in cartography has been the focus of a great deal of attention in GIS (Noël 1978, Lemenkova, 2021), due to their capabilities in optimisation of mapping workflow by scripting. Scripts have some other unique advantages, such as distributed performance of tasks, increased speed of mapping, minimized handmade routine. Such advantages are achieved in using both GMT and GRASS GIS as advanced software applied simultaneously in this study.

5 RESULTS AND DISCUSSION

The results of this study demonstrate the applicability of a novel ML methods of GRASS GIS to satellite image processing and environmental land cover types of analyses in Niger, and the advantages of four ML algorithms of supervised classification are compared to the unsupervised clustering. Land cover patterns in this classification mostly show more distinct differences in the distribution of herbaceous vegetation in the south-western region of Niger than is the case for north-eastern regions with dominating bare areas occupied by sandy deserts. Overall, comparing the strengths and weaknesses of the approaches used for image processing, the ML methods performed better for automated image classification rather than unsupervised clustering. Below we evaluate the performance of the four supervised learning algorithms adopted from the Scikit-Learn ML library of Python, Figs. 6 – 8.

Land cover patterns in central and northern Niger are more associated with geologic setting while southern region is affected by the Niger River basin. The landscape dynamics in the Niger River basin for the studied 10-year period is associated with regional environmental resistance of riparian zone and surrounding region to the climate and hydrological effects (precipitation patterns and frequency of droughts). Moreover, being the principal river of western Africa providing local with essential natural resources, the coastal plains of the Niger River experience intense human impacts such as practice of agro-pastoralism and crop management which affect surrounding landscapes accordingly, Figure 6.

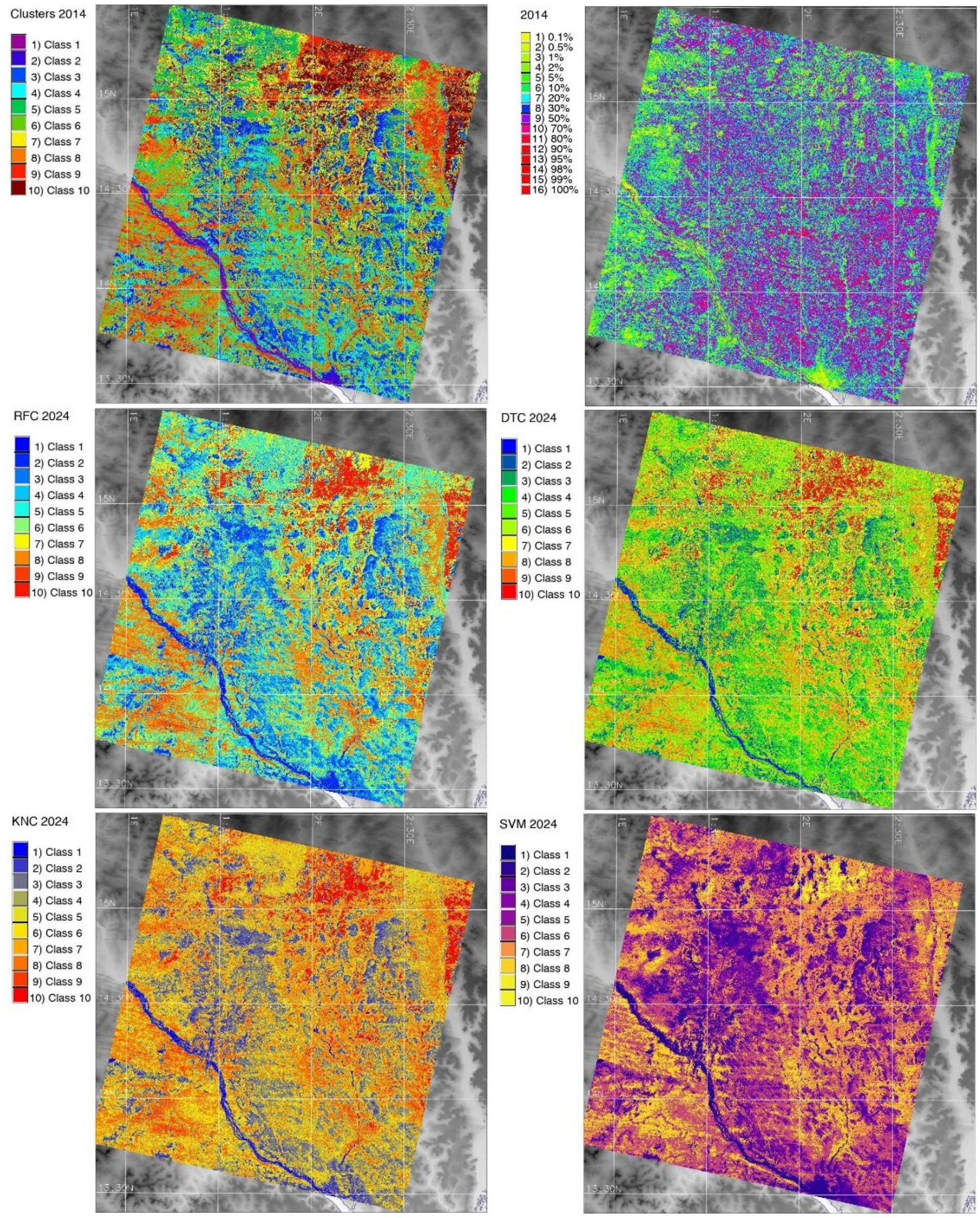

Figure 6 Results of the satellite image processing using classification and ML methods. Region – 1: lowlands in the Niger River basin. Software: GRASS GIS. Map source: author

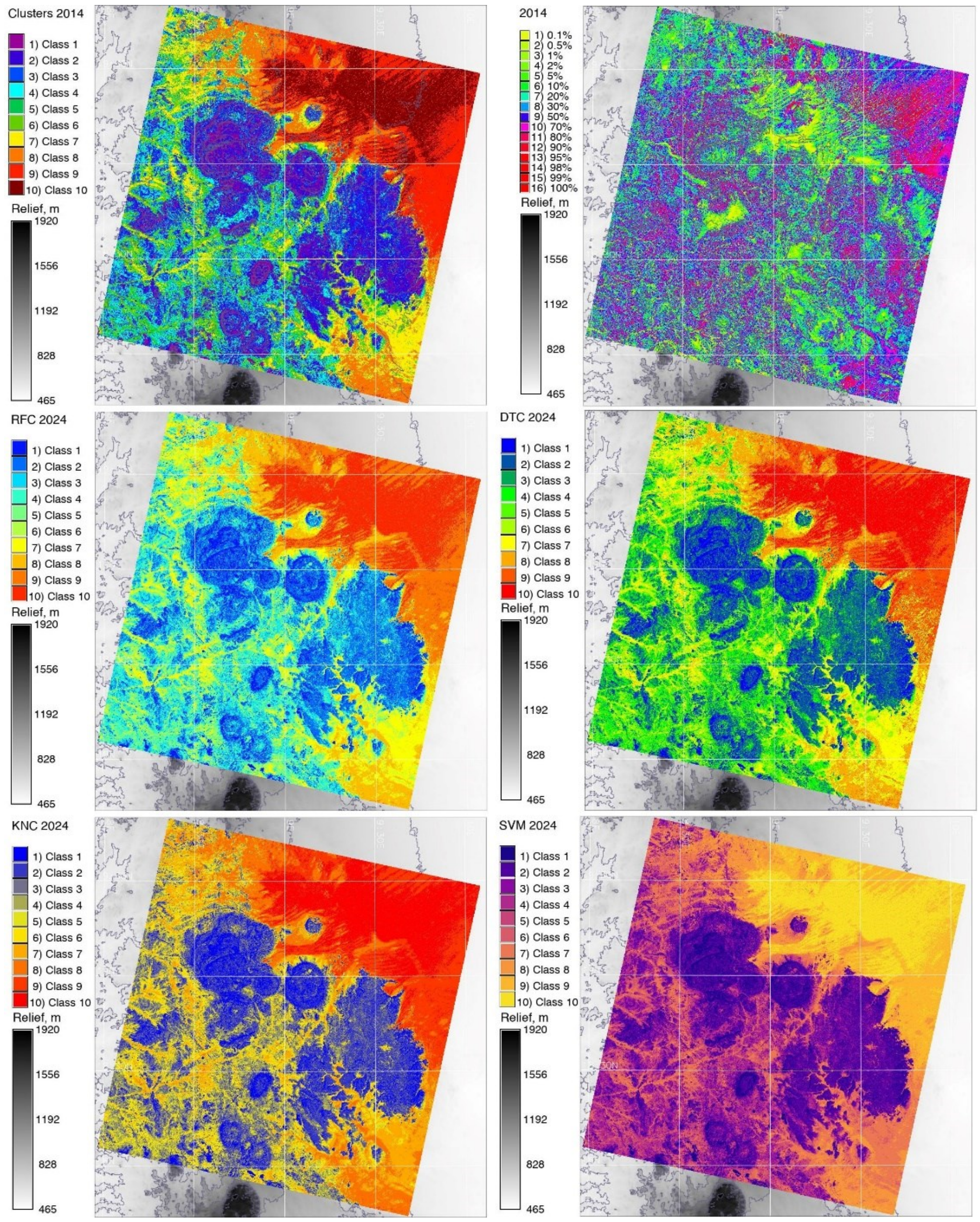

Figure 7 Results of the satellite image processing using classification and ML methods. Region – 2: mountainous area in the Aïr Massif. Software: GRASS GIS. Map source: author

Changes in land cover types in central Niger (Aïr Massif) show which patches experience more fragmentation regarding the distribution of bare rocks, desert sands and vegetated slopes of the mountains during 2014-2024 periods across the region. The difference between the maps performed using different ML algorithms can be summarized as follows. For a classification performed using Random Forest, the algorithms estimate the probability of belonging a selected pixel to specific land cover class. In contrast, the SVM algorithms evaluate the distance to the boundary of these classes with thin Landsat scene, which is then converted to the probability of class using estimation of prediction function by the 'r.learn.predict' module. Hence, for the environmental mapping, SVM generally performs better in terms of precision of pixel's assignment and class separability compared to the Random Forest which is visible for landscapes in Aïr Massif with dominating geologic structures, outcrops and contrasting lithological features, Figure 7.

Nevertheless, Random Forest works well with a mosaic of complex land cover types, such as western Niger which have a mixture of numerical and categorical features. When landscape features are on various scales, such as Djado Plateau, it also performed fine and overall demonstrated the acceptable results. Moreover, Random Forest presents a more straightforward approach to data processing, while SVM maximizes the spatial, that is, geometric, margins of the land cover classes and thus relies on the concept of geospatial distance between pixels that belong to different landscape categories. With this regard, the landscapes with higher class separability and contrasting types (e.g., deserts, vegetated slopes, sands in desert) in northern Niger profit more from the SVM rather them RF classification.

For Djado Plateau in general, the same patterns of land cover types are visible for the ten-year periods for timescales of 2014 to 2024. In Djado Plateau, patterns associated with directions of dunes and eolian conditions are clearly visible and occur in SW-NE direction, which are detected using the computer vision algorithms of GRASS GIS.

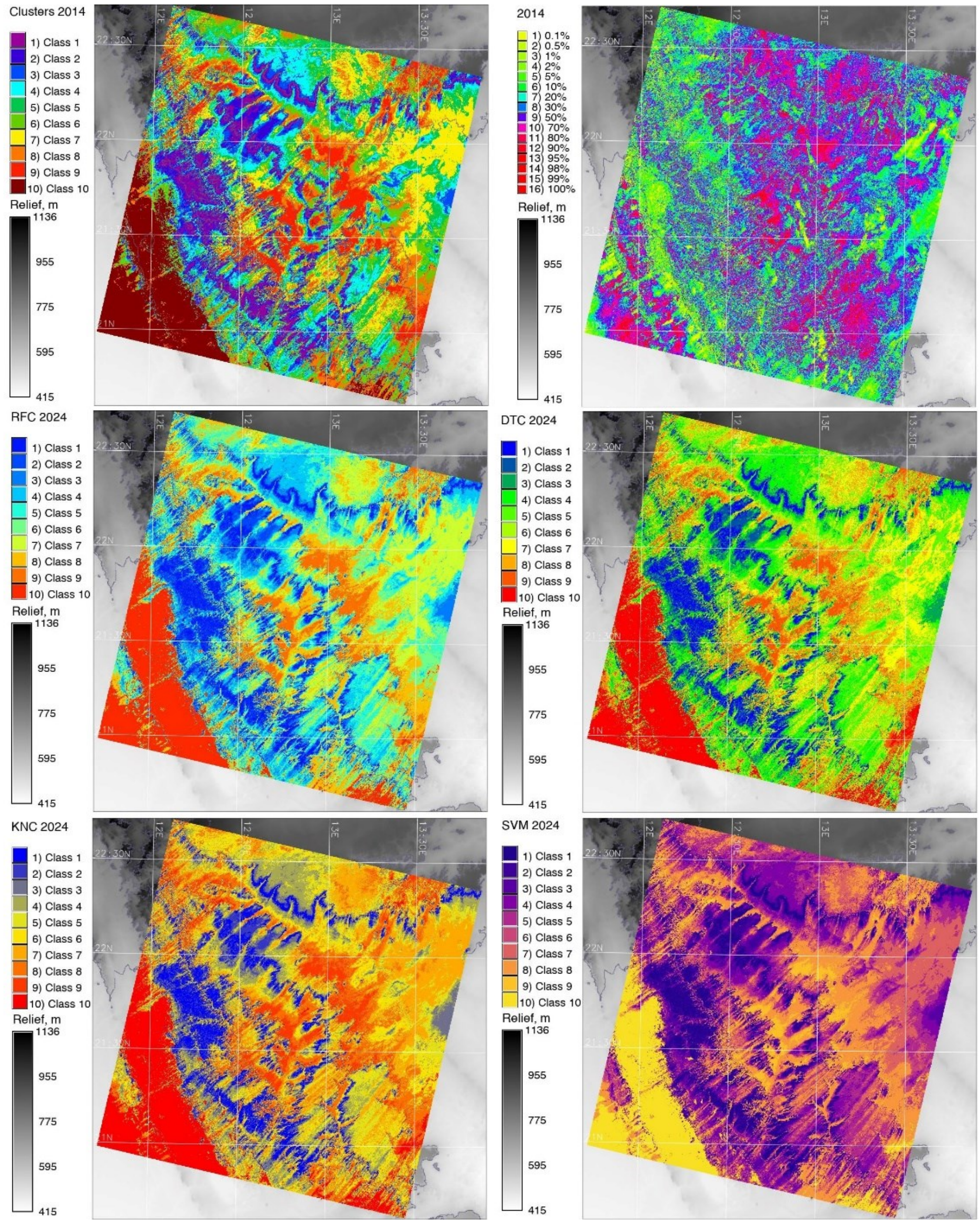

Figure 8 Results of the satellite image processing using classification and ML methods. Region – 3: hills in the Djado Plateau. Software: GRASS GIS. Map source: author

The performance of the Desicion Tree Classifier against the KNeighborsClassifier shown that the Desicion Tree Classifier evaluates the data as hierarchical tree structure where an internal node represents a feature which corresponds to the attributes of landscapes whiel the branch represents a decision rule, and each leaf node represents the outcome with the classified pixels that are assigned to each land cover category, respectively. Hence, the advantages of this algorithm consist in high logical performance and accurate categorization of cells on a raster matrix of Landsat scenes. Regional differences in the land cover patterns associated with geological conditions and detected by the Decision Tree Classifier are shown in Figure 8. As can be noted, the directions of the outcrops here are mostly consist with the stretching of the Ordovician-Cambrian (OCm) formations of central Niger.

The mapping performed using ML algorithms demonstrated superior generalizing capability in terms of image classification, and identification without explicit knowledge supported by training data. Considering the virtues of ML for RS data processing and cartography, with respect to accuracy, speed of data processing and automation, we can conclude that machine learning presents is one of the most perspectives methods for satellite image classification and applications in geoinformatics for environmental mapping. The tuned parameters used for better data processing are constrained by the options of the GRASS GIS which can be compared in terms of time consumption. Thus, there is a significant difference in time which algorithms took for image analysis with SVM being the longest in terms of performance (over 40 minutes) followed by the RF (about 10 minutes). The Decision Tree and K Neighbors Classifiers both performed quickly with completed task within a minute. Besides the technical aspect of data processing, this study also shown the advantages of satellite images for environmental mapping of heterogeneous landscapes of Africa. Namely, a set of six Landsat images is suitable for analysis of landscape patches using GRASS GIS since land cover patterns over Niger show consistency in their distribution for 2014 and 2024 with natural variations driven by climate and environmental forces.

6 CONCLUSION

Landscape dynamics involve environmental regional properties of the land cover types, such as stability and persistence towards external effects (e.g., climate – droughts or flash floods or anthropogenic forces – deforestation, land degradation), and their recovery after such impacts. Therefore, land cover changes are reflected on the space-borne imagery with a wide range of spatio-temporal scales. Such changes are visible, for instance, on time series analysis of the satellite images even for the short-time span (e.g., 10 years as in this study). Hence, shifting mosaic of landscapes towards the steady-state and keeping their resilient properties after the climate effects or human-induced actions can be detectable using a comparison of multi-temporal imagery. In this study, we compared the two scenes (2014 and 2024) for each selected region of Niger (south-west, central and northern regions) to analyze landscapes dynamics on the satellite images Landsat, as well as to evaluate technical performance of various ML algorithms in image processing using GRASS GIS scripting software. The scripting ML method of GRASS GIS is shown to be adequate for RS-based environmental analysis in Niger.

There are several possible directions for future similar research on Niger environment using satellite data. Mapping land cover patterns from higher resolution imagery, such as Sentinel or SPOT data based on time series analysis, in addition to spatial correlation of distribution of land cover types with geologic features, might be useful for geospatial analysis where correlation patterns are notable. Moreover, the methodology reported in this paper could be applied to other regions in Africa in Sahara-Sahel region, and upscaled to worldwide regions with similar arid and semi-arid environment. This is possible using another RS data and satellite imagery with a different data extent. Finally, the predictability of pixels assigned to diverse land cover classes as categories automatically discriminated by computer vision and ML approaches can be investigated further using other algorithms, e.g., Extra Trees Regressor, Gradient Boosting Classifier MLPClassifier and the like. The focus of such research extension would be on the evaluating the effects from drought patterns on the dynamics of land cover types in diverse regions of Africa.

The cartographic interpretations of the land cover type in Niger obtained from the satellite image analysis presented in this study present the qualitative evaluation of landscape dynamics in central Africa. This study contributes to the environmental monitoring of Sahara-Sahel region and presents a useful ML-based approach to RS data processing aimed at reflecting the variability of spatial patterns in Niger caused by climate effects and human activities in the three representative study areas: lowlands of the Niger River basin, mountainous area with the Aïr Mountains and the highlands of the Djado Plateau. The presented series of maps as a result of the outcome of satellite image processing might be of interest to environmental planners and policy makers in suggesting land management in Niger. Besides, actual geo-information on land surface dynamics in the diverse areas of Niger processed by advanced tools of geo spatial analysis is an essential input for sustainable development of Niger and the use of its rich geologic resources. Further, a study on time series analysis of Earth observations data such as Landsat imagery assists in understanding of the environmental and landscape dynamics of the Sahara-Sahelian region of West Africa.

REFERENCE

CHARDON, D. (2023). Landform-regolith patterns of Northwestern Africa: Deciphering Cenozoic surface dynamics of the tropical cratonic geosystem. Earth-Science Reviews 242(104452). https://doi.org/10.1016/j.earscirev.2023.104452

DENIS, M. et al. (2007) The origin and glaciodynamic significance of sandstone ridge networks from the Hirnantian glaciation of the Djado Basin (Niger). Sedimentology 54, pp. 1225-1243. https://doi.org/10.1111/j.1365-3091.2007.00879.x

DIONE, C. et al. (2014) Phenomenology of Sahelian convection observed in Niamey during the early monsoon. Quarterly Journal of the Royal Meteorological Society 140, pp. 500–516. https://doi.org/10.1002/qj.2149

DIOUF, A. et al. (2012) Relationships between fire history, edaphic factors and woody vegetation structure and composition in a semi-arid savanna landscape (Niger, West Africa). Applied Vegetation Science 15, pp. 488-500. https://doi.org/10.1111/j.1654-109X.2012.01187.x

DODO, A. and ZUPPI, G.M. (1997) Étude des écoulements souterrains dans le bassin de Bilma-Djado à l'aide des isotopes de l'environnement. Comptes Rendus de l'Académie des Sciences – Series IIA – Earth and Planetary Science 325(11), pp. 845-852. https://doi.org/10.1016/S1251-8050(99)80184-0

DODO, A. and ZUPPI, G.M. (1999) Variabilité climatique durant le Quaternaire dans la nappe du Tarat (Arlit, Niger). Comptes Rendus de l'Académie des Sciences – Series IIA – Earth and Planetary Science 328(6), pp. 371-379. https://doi.org/10.1016/S1251-8050(99)80102-5

EMETERE, M.E. and AKINYEMI, M.L. (2017) Documentation of atmospheric constants over Niamey, Niger: a theoretical aid for measuring instruments. Meteorological Applications, 24, pp. 260-267. https://doi.org/10.1002/met.1624

FAVREAU, G. et al. (2009) Land clearing, climate variability, and water resources increase in semiarid southwest Niger: A review. Water Resources Research 45 (W00A16). https://doi.org/10.1029/2007WR006785

FELIX-HENNINGSEN, P. (2000) Paleosols on Pleistocene dunes as indicators of paleo-monsoon events in the Sahara of East Niger. CATENA 41(1), pp. 43-60. https://doi.org/10.1016/S0341-8162(00)00108-9

GOND, V. et al. (2004) Surveillance et cartographie des plans d'eau et des zones humides et inondables en régions arides avec l'instrument VEGETATION embarqué sur SPOT-4. International Journal of Remote Sensing 25(5), pp. 987–1004. https://doi.org/10.1080/0143116031000139908

HAROUNA, M. and PHILP, R.P. (2012) Potential Petroleum Source Rocks in the Termit Basin, Niger. Journal of Petroleum Geology 35, pp. 165-185. https://doi.org/10.1111/j.1747-5457.2012.00524.x

INGRAM, G.B. 1990. Multi–gene-pool Surveys in Areas with Rapid Genetic Erosion: An Example from the Aïr Mountains, Northern Niger. Conservation Biology 4, pp. 78-90. https://doi.org/10.1111/j.1523-1739.1990.tb00270.x

JUSTICE, C.O. and HIERNAUX, P.H.Y. (1986) Monitoring the grasslands of the Sahel using NOAA AVHRR data: Niger 1983. International Journal of Remote Sensing 7(11), pp. 1475–1497. https://doi.org/10.1080/01431168608948949

KEELING, D.J. (2009) Photojournal: The Sahara and Sahel, Peoples and Places in a Fragile Environment. Focus on Geography 51, pp. 17-22. https://doi.org/10.1111/j.1949-8535.2009.tb00236.x

LASAGNA, M. et al. (2015) Georesources and Environmental Problems in Niamey City (Niger): A Preliminary Sketch. Energy Procedia 76, pp. 67-76. https://doi.org/10.1016/j.egypro.2015.07.848

LEMENKOVA, P. (2021) Geophysical Mapping of Ghana Using Advanced Cartographic Tool GMT. Kartografija i Geoinformacije 20(36), pp. 16-37. https://doi.org/10.32909/kg.20.36.2

LEMENKOVA, P. (2022a) Tanzania Craton, Serengeti Plain and Eastern Rift Valley: mapping of geospatial data by scripting techniques. Estonian Journal of Earth Sciences 71, pp. 61–79. https://doi.org/10.3176/earth.2022.05

LEMENKOVA, P. (2022b) Mapping submarine geomorphology of the Philippine and Mariana trenches by an automated approach using GMT scripts. Proceedings of the Latvian Academy of Sciences. Section B. Natural, Exact, and Applied Sciences 76, pp. 258–266. https://doi.org/10.2478/prolas-2022-0039

LEMENKOVA, P. (2023a) A GRASS GIS Scripting Framework for Monitoring Changes in the Ephemeral Salt Lakes of Chotts Melrhir and Merouane, Algeria. Applied System Innovation 6(4), pp. 61. https://doi.org/10.3390/asi6040061

LEMENKOVA, P. (2023b) Monitoring Seasonal Fluctuations in Saline Lakes of Tunisia Using Earth Observation Data Processed by GRASS GIS. Land 12(11), pp. 1995. https://doi.org/10.3390/land12111995

LEMENKOVA, P. (2023c) Using open-source software GRASS GIS for analysis of the environmental patterns in Lake Chad, Central Africa, Die Bodenkultur: Journal of Land Management, Food and Environment 74(1), pp. 49-64. https://doi.org/10.2478/boku-2023-0005

LEMENKOVA, P. (2023d) A GRASS GIS Scripting Framework for Monitoring Changes in the Ephemeral Salt Lakes of Chotts Melrhir and Merouane, Algeria. Applied System Innovation 6(4), pp. 61. https://doi.org/10.3390/asi6040061

LEMENKOVA, P. and DEBEIR, O. (2023) Time Series Analysis of Landsat Images for Monitoring Flooded Areas in the Inner Niger Delta, Mali. Artificial Satellites 58(4), pp. 278-313. https://doi.org/10.2478/arsa-2023-0011

MCSHANE, T.O. (1987) Elephant-fire relationships in Combretum/Terminalia woodland in south-west Niger. African Journal of Ecology 25, pp. 79-94. https://doi.org/10.1111/j.1365-2028.1987.tb01095.x

MAMANE BARKAWI, M.B. et al. (2023) Using Multisensor Earth Observation Data to Understand the Development of the Kourtéré Kori Alluvial Fan and Its Impact on the Hydrology of the Niger River. The Professional Geographer 75(5), pp. 715–732. https://doi.org/10.1080/00330124.2023.2183415

MAMANE MAMADOU, M. et al. (2020) Cenozoic oxidation episodes in West Africa at the origin of the in situ supergene mineral redistribution of the primary uranium orebodies (Imouraren deposit, Tim Mersoï Basin, Northern Niger). Mineralium Deposita 55, pp. 1333–1352. https://doi.org/10.1007/s00126-019-00945-w

MEISTER, C. et al. (1994) Nouvelles données sur lesammonites du Niger oriental (Ténéré, Afrique occidentale) dans le cadre de la transgression du Cénomanien-Turonien. Geobios 27(2), pp. 189-219. https://doi.org/10.1016/S0016-6995(94)80006-5

MERGL, M. and MASSA, D. (2000) Chapter 4 – A Palaeontological Review of the Devonian and Carboniferous Succession of the Murzuq Basin and the Djado Sub-Basin. In: SOLA, M.A. and WORSLEY, D. Geological Exploration in Murzuq Basin, pp. 41-88. https://doi.org/10.1016/B978-044450611-5/50006-4

MERING, C. et al. (2010) Retrieving urban areas on Google Earth images: application to towns of West Africa. International Journal of Remote Sensing 31(22), pp. 5867–5877. https://doi.org/10.1080/01431161.2010.512311

MOLINA, G., GABER, A. and EL-BAZ, F. (2017) Mapping palaeolakes in the Ténéré Desert of northeastern Niger using space-borne data for groundwater potential. NRIAG Journal of Astronomy and Geophysics 6(2), pp. 395–407. https://doi.org/10.1016/j.nrjag.2017.10.001

MULDERS, M.A. and GIRARD, M.C. (1993) Remote sensing of soils in warm arid and semi-arid lands. Remote Sensing Reviews 7(3–4), pp. 341–363. https://doi.org/10.1080/02757259309532185

Noël J., 1978. Cartographie automatique des surfaces en eau libre. La Houille Blanche 64(7-8), pp. 527–532. https://doi.org/10.1051/lhb/1978043

OGUNTUNDE, P.G. et al. (2014) Modelling the impacts of reforestation on the projected hydroclimatology of Niger River Basin, West Africa. Ecohydrology 7, pp. 163-176. https://doi.org/10.1002/eco.1343

OSTROWSKI, S., MASSALATCHI, M.S. and MAMANE, M. (2001) Evidence of a dramatic decline of the red-necked ostrich Struthio camelus camelus in the Aïr and

Ténéré National Nature Reserve, Niger. Oryx 35, pp. 349-352. https://doi.org/10.1046/j.1365-3008.2001.00205.x

SANI, A. et al. (2022) Tectono-Sedimentary Evolution of the Uranium Deposits in the DASA Graben (Northern Niger). In: MEGHRAOUI, M. et al. Advances in Geophysics, Tectonics and Petroleum Geosciences. CAJG 2019. Advances in Science, Technology & Innovation. Springer, Cham. https://doi.org/10.1007/978-3-030-73026-0_144

SPONHOLZ, B. (1994) Silicate karst associated with lateritic formations (examples from eastern Niger). CATENA 21(2), pp. 269-278. https://doi.org/10.1016/0341-8162(94)90017-5

TIEPOLO, M. and GALLIGARI, A. (2022) Dataset on the expansion and consolidation of flooded settlements in the Dosso Region, Niger. Data in Brief 41, pp. 107935. https://doi.org/10.1016/j.dib.2022.107935

VERDIN, J.P. (1996) Remote sensing of ephemeral water bodies in western Niger. International Journal of Remote Sensing 17(4), pp. 733–748. https://doi.org/10.1080/01431169608949041

VIVIROLI, D. et al. (2007) Mountains of the world, water towers for humanity: Typology, mapping, and global significance. Water Resource Research 43, pp. W07447. https://doi.org/10.1029/2006WR005653

WYLIE, B.K. et al. (1992) A satellite-based range assessment system for the Sahel of Africa. Geocarto International 7(1), pp. 79-85. https://doi.org/10.1080/10106049209354355

ZANGUINA, M., BRUNETON, A. and GONNARD, R. (1998) An Introduction to the Petroleum Potential of Niger. Journal of Petroleum Geology 21, pp. 83-103. https://doi.org/10.1111/j.1747-5457.1998.tb00647.x

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OPTIMIZATION OF VENTILATION USING IIOT METHODOLOGY IN SERBIAN COAL MINES

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Abstract: The application of information technologies in the optimization of ventilation contributes significantly to the improvement of all aspects of mine operations. Coal mines face numerous challenges on a daily basis in terms of the organization, implementation and supervision of production activities. Some global mining companies have already implemented numerous technical solutions in the field of robotics, artificial intelligence and the Internet of Things (IoT). This article describes the basic principles of the Industrial Internet of Things (IIoT) and the configuration of the automation system for ventilation. It also discusses the opportunities and challenges of technology implementation in the coal mine. The advantages of applying modern software tools for monitoring mine air parameters and monitoring the operating characteristics of the main ventilation systems in real time greatly facilitate the control of working conditions in the mine. On this basis, it is possible to create a package of preventive and active measures in the event of equipment faults, fires or sudden gas outbursts.

Keywords: IIoT, coal mine ventilation, automation

1 INTRODUCTION

The mining industry is concerned with the production of raw materials. These are necessary for the functioning of other industries as well as for the functioning of a country's economy and its smooth development. In order to optimize their operations, companies must overcome numerous challenges related to safety, production organization, coordination of work tasks and management of business units within the company's organized work structure.

The automation of mining production processes optimizes the operation of the mine, which achieves outstanding business results at significantly reduced costs and in compliance with occupational health and safety standards. The current database, which

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is stored in real time, serves as the basis for classifying, interpreting, trending and visualizing the information collected on the monitored process.

The Internet of Things (**IoT**) is a term that unites the virtual world with devices of varying degrees of complexity and technical systems that surround us. The data in the virtual world is processed by software based on a variety of methods and algorithms. The Industrial Internet of Things is a further development of the **IoT**, the main difference being that the **IoT** focuses on the individual needs of users, while the **IIoT** aims to increase the efficiency, safety and profitability of industrial activities (POLIMAK).

The described technology is part of a broader concept called Industry 4.0, which is a new phase of the industrial revolution that promotes digital technologies, artificial intelligence, interconnectivity of devices and machines, internet-based communication and real-time data collection.

The integration of the information technology system into the operational industrial system is a complex process. This requires the introduction of industrial standards for the implementation of technical solutions for process automation in the industrial sector.

The introduction of uniform communication protocols is necessary to enable the standardization of the devices used. This will promote the further improvement and modernization of industrial technologies.

Based on the previous explanation, the basic components of the IIoT operating system can be distinguished (POLIMAK):

- Cloud Computing,
- Wireless Internet,
- Input/Output,
- Artificial intelligence (Machine learning, Artificial Neural Network, ...).

The basic structure of the Industrial System for managing the technological process in real time is shown in Figure 1. Communication within the individual blocks and between the blocks at different levels takes place through industrial protocols, as shown in Figure 2 (Singha, A. et al., 2018). The structures created in this way make it possible to shorten the operating time if the ventilation parameters deviate from the designed ones. Time to action is crucial in cases of sudden gas burst.

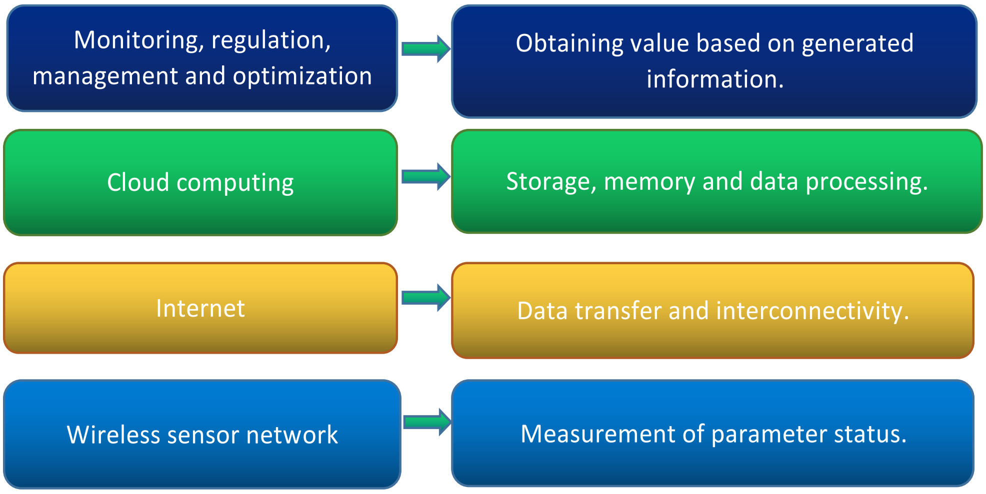

Figure 1 Structure of the Industrial Internet of Things system for real-time management

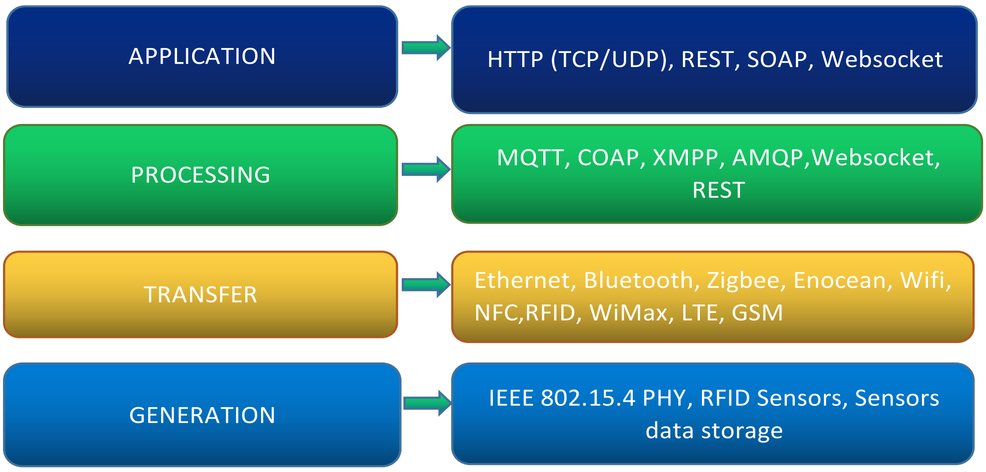

Figure 2 Industrial protocols for communication (Singha, A. et al., 2018)

The development of a high-quality ventilation system requires constant monitoring, recording, processing and re-implementation into the process. The use of suitable software enables rapid data processing and real-time action. The advantage of using such a system is very significant from a safety point of view, which eliminates the presence of workers in polluted mine air when the operating parameters of auxiliary fans in the mine need to be corrected and the air distribution needs to be regulated according to the conditions on site.

2 APPLICATION OF IIOT METHODOLOGY FOR VENTILATION OPTIMIZATION

The strategy of technological process management aims to monitor all influential process units, regulate input parameters, collect data on the state between input and output parameters and make timely management decisions that optimize the process itself. The data is updated in real time, which provides an insight into the status of working conditions on site. On this basis, it is possible to react in a timely manner and prevent the occurrence of potential risky situations.

The detection of possible irregularities in the operation of the machines, the functioning of the process or its component unit, is made possible thanks to the integrated sensors. The sensors record the values of the corresponding observed variables. The alarm system alerts the team in the control room to the presence of a possible malfunction in the equipment, and the user of the system takes management activities. Effective communication prevents situations that endanger the safety of the workers.

The development of optimized ventilation systems is a necessary prerequisite for safe working in mines. In order to ensure a sufficient supply of fresh air in all parts of the mine, it is important to develop a sustainable ventilation design. In addition, the work carried out must be consistent with the assumed design. Monitoring the working environment in real time is crucial to ensure safe working conditions. It is also important to modernize the technology of control and regulation of working parameters in the mine.

The application of modern software tools for monitoring mine air parameters and monitoring the operating characteristics of the main ventilation systems in real time makes it much easier to control the working conditions in the mine. This leads to more efficient production management in compliance with the legal framework. An up-to-date database, the possibility of preventive measures and a complete insight into the state of the mine atmosphere are just some of the benefits offered by these software packages. Prior professional training of personnel is required to use this software.

2.1 Predictive maintenance of fans and related ventilation equipment

Monitoring of the technical correctness of ventilation devices and the timely elimination of equipment failures has a significant impact on improving safety. The company Zitrón offers a system for optimizing ventilation in mines, which leads to better working conditions, a reduction of carbon emissions and a reduction of mine energy consumption (up to 40%). These could be the highest energy costs that mines have (Zitrón, 2021).

Most mines do not have an optimized ventilation design. It is necessary to determine the actual required airflow for the entire mine as well as the required air volumes for certain parts of the mine in the appropriate period. Based on the relevant performance indicators of the ventilation systems and the sustainability of the adopted technical solutions, a plan for automating the ventilation of the mine can be created. Thanks to its flexibility and practicality, the system can be integrated into the existing mine communication system. Figure 3 shows a display of fan operating parameters, which monitors air flow, power input, bearing temperature, and air temperature. Based on recorded data the preventive maintenance can be organized.

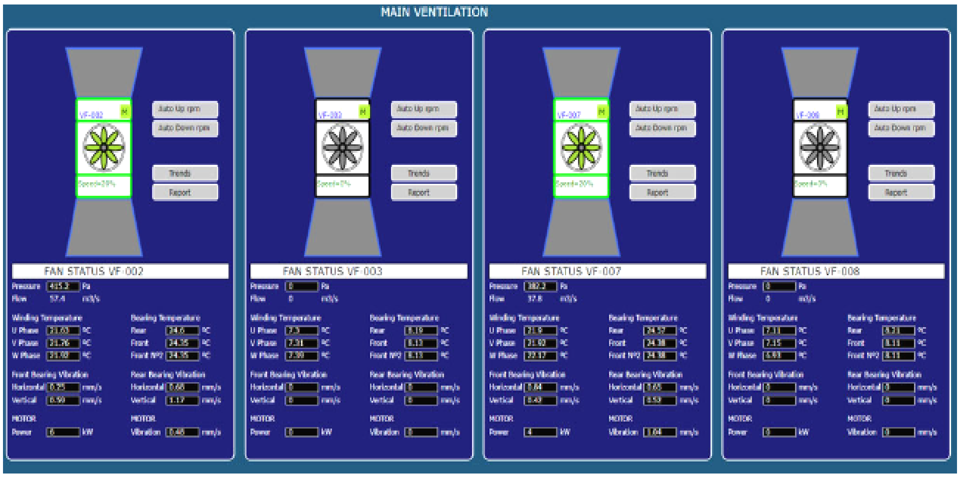

Figure 3 Monitoring of fan operating parameters in real time (Zitrón, 2021)

2.2 Wireless sensor network for gas monitoring

The gas concentration sensors are used to collect important data on working conditions. The data is transmitted to the main base in the mine via a wireless network. From there, it is sent to the main control station on the surface via wired network protocols. Based on the data obtained, useful information is generated about the production process and aspects of safety and efficiency of the realized production plans.

During blasting, a large amount of harmful and toxic gases are released and the oxygen concentration changes. The GuardIAN Intelligence Network from MineARC Systems offers a suitable solution for re-entry scenario after blasting. Based on the data obtained from the sensors, a decision is made on the safe time to return to the worksite after blasting is made. The sensors automatically confirm with a light signal that the conditions have been met for workers to return to the workplace. The lighting nodes warn the workers if the zone is unsafe for work. The previous practice was that checking the safety of the work zone required the arrival of workers who used detection devices to check the gas condition, often several times before the working conditions were met. This procedure takes too much time and is risky for the safety and health of workers (MineARC Systems, 2021).

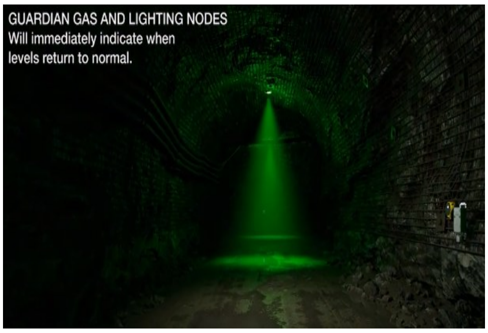

Figure 4 GuardIAN Intelligence Network sensors for gas concentration measurement and light signaling of safety conditions at the workplace (MineARC Systems, 2021)

In practice, sensors that register the gas concentration at workplaces (CO, CO2, CH4) or the air temperature provides data in real time, on the basis of which the ventilation system is automatically adjusted depending on what work is being carried out, how many workers are at the workplace, etc.

2.3 Interconnectivity and continuous communication

In underground coal mining, in order to maintain effective communication in complex working conditions it is necessary to adopt modern digital communication and connectivity technology. This ensures interoperability and the timely undertaking of management activities. A robust infrastructure of information technologies harmonized with the requirements of the industrial application enables effective communication between the different structural levels of the company. The acquisition of data from portable devices and wireless sensors at work sites, their interpretation and visualization significantly shorten the time for generating key information about mine production.

Unhindered communication is the basis for optimizing all technological phases of underground exploitation. This is the main reason for considering ventilation as an indispensable part of all other technological phases and not as an isolated unit in mine production.

ABB Smart Ventilation offers several levels of monitoring, control and optimization. The system is based on the 800xA platform. Some of the main advantages of the proposed system architecture are modularity, flexibility and scalability. The European metal company Boliden opted for the above-mentioned automation system, reducing costs by 30% (ABB).

2.4 Related work

Jo, B., and Khan, R.M.A. (2018) propose the application of the Internet of Things system for the monitoring and assessment of air quality in mines. In addition to data on the current values of air properties, the system also has the ability to predict air quality based on machine learning. The most important elements of this system are:

- Sensors for measuring humidity, temperature, carbon dioxide (CO2), carbon monoxide (CO), methane (CH4), sulfur dioxide (SO2), hydrogen sulfide (H2S) and nitrogen dioxide (NO2),
- Machine learning platform (Azure Machine Learning Platform) that predicts air quality in mines
- Statistical methods for evaluating the most influential variables.

Ali, M. H. et al. (2018) presented an IoT dynamic system for monitoring workers' health through sensors attached to workers' helmets. Data on the condition of the air is always available. If the permissible values of the observed parameters are exceeded, the alarm system is activated. This is followed by appropriate feedback from the monitoring team to restore safe and healthy working conditions.

Wu, Y. et al. (2022) expanded the system of IoT technologies by adding a platform for processing a large package of diverse data (big data). In this way, a dynamic information platform for collecting, classifying, storing, processing and interpreting data on all aspects of mine safety was created.

Anani, A. et al. (2024) reviewed application of machine learning methods for the prediction of coal and gas outbursts in underground mines. Machine learning-based models use a data-driven approach. Data is collected using AE (acoustic emission), EMR (electromagnetic radiation) and gas sensors. Based on the processed data, a model with high prediction accuracy is selected. Numerous factors are taken into account for the prediction of eruptions. They can be classified into the following categories: geological, gas, coal seam and operational. The application of predictive models is important to reduce the risk of hazards in the mine. The implementation of a real-time monitoring sensor system will increase data quality.

Muduli, L. et al. (2018) investigated the application of wireless sensor networks for environmental monitoring in underground coal mines. In this study, WSN technology is also considered for monitoring mine hazards, personnel and equipment. In underground coal mines, there are many contaminants such as explosive gases, toxic gases, acute toxic gases, coal dust and water vapor. Changes in observed parameters such as gas and dust concentration, temperature, humidity and air pressure can increase the risk to the safety and health of miners. It is therefore necessary for mines to incorporate technologies such as the Internet of Things.

3 PROPOSED IIOT ARCHITECTURE

Effective control of parameters and indicators of air quality in the mine is achieved when the impact of other relevant factors of the technological process is taken into account, which primarily refers to the applied mining method, the transportation machines used, the coordination of workers, machines and accompanying equipment, the drainage system and other significant segments of production.

The automation of ventilation, the monitoring of the parameters of the substructure elements, the machines used for digging, loading and transportation of coal, as well as the health of the workers, significantly contribute to an informed management of the production and business aspects of the mine, better coordination and communication at the various management levels. In this way, the highest standards of occupational health and safety, maximum production capacity and economic operation of the mine are achieved. The energy efficiency and reliability of the sensors are the main characteristics that set them apart from other conventional technologies for monitoring the working environment.

Underground coal mining in Serbian mines is still characterized by low-productivity mining methods. Therefore, it is necessary to adapt the resources for the implementation of innovative technologies to the limitations that each mine has. This does not mean that coal mines should be excluded from the consideration of the possible digitalization of the business, but they should be approached with even greater attention and interest in order to find the optimal solution.

Traditional methods of data collection, management and regulation of ventilation do not provide optimal results. The isolation of individual subsystems within the business system has led to a significant delay in the transmission of information, resulting in significant deviations from planned production and business activities.

In underground coal mining, in addition to energy efficiency, maintaining effective communication under complex working conditions is essential. The use of modern digital communication and connectivity technology guarantees interoperability and the timely undertaking of management activities. The main advantage of such a system is its continuous improvement thanks to the constant flow of information and networking of all important aspects of the mine. The proposed IIoT architecture for the optimization of underground coal mine ventilation is shown in Figure 5.

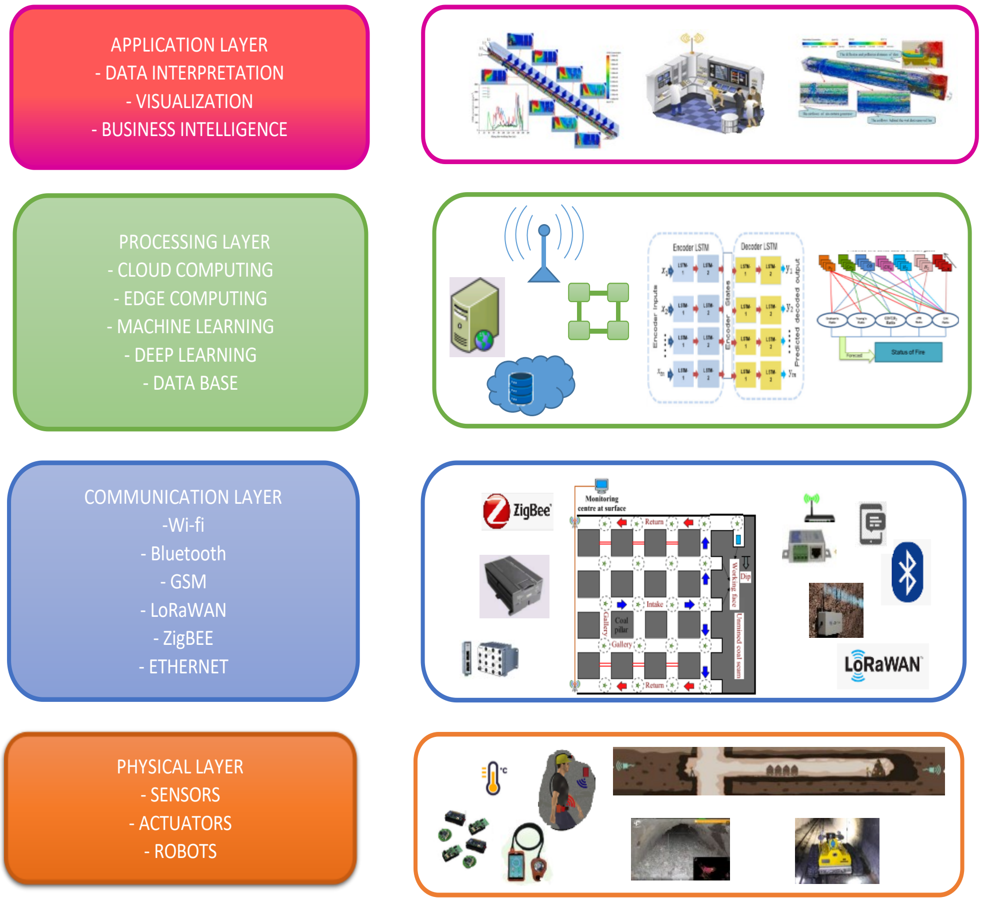

Figure 5 Proposed IIoT architecture for a coal mine ventilation optimization

The real-time management structure presented can be implemented in the existing mine production system. In this way, it is possible to monitor the operating parameters of the fan, the quality of the mine air and compare the values obtained with the data from other processes in the mine. In addition, by using smart devices information is obtained about the position, health and safety of workers.

4 DISCUSSION

In order to maintain the functionality of the system, the devices must withstand the difficult working conditions in the mine, which are reflected in a wide range of changes in operating temperature, high humidity, vibrations, noise and dust.

The lack of standardization of IIoT architecture has a negative impact on the security of network operations and threatens the security of critical mine operation data. In addition, difficult working conditions call into question the correct operation of the components of the communication system. Considering the above-mentioned shortcomings, it is crucial to design equipment that can withstand large fluctuations in temperature, humidity and other variable parameters in the mine.

Complex conditions, which are also reflected in the frequent changes in the position of the workplace, make the development of the communication system particularly difficult. These factors hinder the functionality of the system. This manifests itself in interrupted data transmissions and poor connectivity between devices.

The challenges in the implementation of IIoT technology are expressed in the methodology of finding a technical solution which will harmonize the industrial requirements of the mine and the requirements of information technology. To successfully design a system that ensures the optimization of production, a team of experts from the fields covered by the industrial concept of the Internet of Things is required.

The establishment of such a system would significantly improve the System safety. It would also increase productivity by reducing the time spent away from the workplace. The energy savings would be considerable as other phases of the operating process could also be harmonized based on the ventilation parameters. The end result would be a reduction in operating costs.

5 CONCLUSION

The implementation of modern digital technologies offers numerous benefits and enables the further improvement and development of sustainable mining. By integrating information systems into the business structure of the mine, the basic concepts of automation are fulfilled. They are implemented through management, supervision, regulation and optimization of the technological process. The highest standards of occupational health and safety are set, and maximum productivity is achieved. Resource utilization is also achieved, encouraging further improvement of existing exploitation technologies and examination of the possibilities of new approaches to the exploitation of mineral resources.

The introduction of the real-time monitoring, control and action system for the ventilation system as one of the most important activities in coal mining creates the conditions for optimizing other phases of coal production. There is an opportunity to expand both the transportation and dewatering systems. In this way, the entire mining system would be monitored in real time, which would avoid production losses and increase productivity.

By investing in adequate resources for the design and development of communication systems in the mining industry, an optimized business model is created. This implies a timely and informed management of the company's business based on information about the production segments observed.

REFERENCES

POLIMAK The Differences between IoT and IIoT. [Online] POLIMAK. Available from: https://polimak.com/en/the-differences-between-iot-and-iiot-iot-vs-iiot/[Accessed 06/09/24]

SINGHA, A., KUMAR, and D., HÖTZEL, J. (2018) IoT Based information and communication system for enhancing underground mines safety and productivity: Genesis, taxonomy and open issues in Ad Hoc Networks. 2018, no. 78, pp. 115-129, https://doi.org/10.1016/j.adhoc.2018.06.008

ZITRON (2021) Mining automation, Innovation towards autonomous mining. [Online] ZITRON. Available from: https://zitron.com/mining-automation-for-underground-ventilation-systems/ [Accessed 09/09/24]

MINEARC SYSTEMS (2021) Guardian Intelligence Network - Re Entry Scenario. [Online] MineARC Systems. Available from: https://www.youtube.com/watch?v=g_m5d_PHCbM [Accessed 09/09/24]

ABB System 800xA mine ventilation control at Boliden [Online] ABB. Available from: https://new.abb.com/control-systems/industry-specific-solutions/mining/system-800xa-for-mine-ventilation-control-boliden [Accessed 09/09/24]

JO, B., and KHAN, R.M.A. (2018) An Internet of Things System for Underground Mine Air Quality Pollutant Prediction Based on Azure Machine Learning in Sensors. 2018, no. 4, 930. https://doi.org/10.3390/s18040930

ALI, M. H. et al. (2022) Improving coal mine safety with internet of things (IoT) based Dynamic Sensor Information Control System in Physics and Chemistry of the Earth. 2022, 128, 103225. https://doi.org/10.1016/j.pce.2022.103225

WU, Y. et al. (2018) A dynamic information platform for underground coal mine safety based on internet of things in Safety Science. 2018, 113, pp. 9-18. https://doi.org/10.1016/j.ssci.2018.11.003

MUDULI, L. et al. (2017) Application of wireless sensor network for environmental monitoring in underground coal mines: A systematic review in Journal of Network and Computer Applications. 2017, 106, pp. 48-67. https://doi.org/10.1016/j.jnca.2017.12.022

SADEGHI, S., SOLTANMOHAMMADLOU, N., and NASIRZADEH, F. (2022) Applications of wireless sensor networks to improve occupational safety and health in underground mines in Journal of Safety Research. 2022, 83, pp. 8–25. https://doi.org/10.1016/j.jsr.2022.07.016

CAO, Y. et al. (2024) Recent progress and perspectives on coal dust sources, transport, hazards, and controls in underground mines in Process Safety and Environmental Protection. 2024, 187, pp. 159–194. https://doi.org/10.1016/j.psep.2024.04.095

ANANI, A. et al. (2024) Advancements in machine learning techniques for coal and gas outburst prediction in underground mines in International Journal of Coal Geology. 2024, 285, 104471. https://doi.org/10.1016/j.coal.2024.104471

DEY, P. et al. (2021) Hybrid CNN-LSTM and IoT-based coal mine hazards monitoring and prediction system in Process Safety and Environmental Protection. 2021, 152, pp. 249-263. https://doi.org/10.1016/j.psep.2021.06.005

LANNER (2024) Rugged wireless gateway for underground mine monitoring [Online] Lanner. Available from: https://lannerinc.com/applications/intelligent-systems/rugged-wireless-gateway-for-underground-mine-monitoring [Accessed 09/09/24]

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Professional paper

LABORATORY RESEARCH FOR THE CHEMICAL EOR PROJECTS. CASE STUDY IN SERBIA

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Abstract: During analysis of work process after first chemical EOR project done in Serbia it was observed that our available resources were not used in an optimal way. Some of laboratory tests that were part of standard testing procedures for selection of chemicals gave us little or non-useful information but took a lot of time and resources. This drove us to analyze all our available resources and to develop a process algorithm that will give us best "value for money spent" in terms of time optimization, and developing testing methodology that will utilize equipment that is already available in our laboratory. In a way, entire process was adapted to local conditions – focusing on conditions in Serbian oilfields and chemical selection methods needed for those conditions. The process described here is applied after chemical EOR method selection and it covers all possible combinations: Surfactant, Polymer, SP or ASP EOR. In case that one component is excluded, workflow can be modified with ease.

Keywords: chemical EOR; laboratory tests, polymer surfactant selection, core flood tests

1 INTRODUCTION

There is a greater need to enhance oil recovery from oilfields that are already in production because primary and secondary methods of oil production can only extract a limited portion of the original oil in place (OOIP) and because most large oilfields are in the late stages of production. Cost-effective ways to increase production are required because traditional oil production techniques leave a lot of oil in reservoirs. Chemical enhanced oil recovery (cEOR) techniques are used to accomplish this goal. They involve injecting alkali, surfactant, and polymer either separately or in combination (ASP) into a reservoir to mobilize oil that isn't recoverable using traditional production techniques.

Chemical EOR (cEOR) and ASP techniques have been researched and used in a variety of settings worldwide for many years. The general idea remained the same, but during

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this time considerable progress was made in creating products that can be used in challenging reservoir conditions (high salinity, high temperature, and heavy oil). Soap is created when alkali reacts with organic acids that are found naturally in oil (GAO et al., 1995; MAHDAVI & ZEBARJAD, 2018). This newly formed soap and the injected surfactant work together to modify the wettability of porous environments, reduce interphase tension (IFT) between water and oil, and produce a mobile microemulsion that is aided by a viscous polymer front that follows the surfactant (MOHYALDINN et al., 2019; WANG et al., 2007).

In this paper are presented criteria and methods of selection for surfactants, polymers and alkali for cEOR, evaluating characteristics of SP or ASP mixtures and assessing the effects of field applications.

2 CHEMICAL SELECTION METHODS AND CRITERIA FOR CEOR APPLICATIONS

The first step in preparation for cEOR process is selecting the mixing water. In most cases this is not an issue since cEOR methods are tertiary production methods and it is applied after secondary method – water injection. If water injection is applied on a given field, it means that water injection infrastructure is already in place, pipelines, pumping system, etc. and water source as well, being that a formation water or any other kind. In that case chemicals are simply adapted to the available water because it is most convenient. In Serbia, in most of the oilfields strong aquifer is present, it is providing driving energy for production and because of that it is not necessary apply water injection. This is adding additional burden to cEOR project, not only because of water selection, but because it is putting additional cost for setting up entire injection infrastructure, sometimes influencing profitability of entire project.

In general, there are only two sources of water available: technical – potable water from local aquifer or produced formation water for disposal. Technical water has much better quality than formation water but, often it is not available in large quantities, either because local aquifer cannot produce enough water, or it is used by local community for water supply, and it cannot be used for any other purposes. Produced/formation water is available but regulating standards for disposal water and injection water are different and there are always issues with quality.

In most cases formation water is only one available. Issues that can arise with high oil in water content and suspended particles can be solved with additional filtering unit. If there is high content of sulphide reducing bacteria (SRB) biocide needs to be added in water with sufficient concentration to decrease bacteria content to less than 20 cfu/ml. Biocide needs to be compatible with all the other chemicals that will be used in cEOR project, mainly polymer (SERIGHT and SKJEVRAK, 2015; JOUENNE, KLIMENKO and LEVITT, 2016). Oxygen scavenger can be required as well, if oxygen is present in concentration higher than 46 ppb. The chemical composition of formation water cannot be influenced, such as salinity and ferric ion content, and it will influence polymer selection process.

2.1 Polymer selection and testing

The role of polymer in cEOR is to increase viscosity of displacing fluid and increase displacement of residual oil. There have been experiments with both synthetic and biopolymers, such as partially hydrolyzed polyacrylamide polymer (HPAM) and xanthan. Because of their low cost, wide commercial availability, superior viscosity-enhancing performance, and resistance to microbial degradation, HPAM polymers are currently the most used in polymer flooding. As mentioned previously, polymer is influenced by mixing water. Higher salinity requires higher polymer concentration, presence of Fe ions requires sulfonated polymers and presence of oxygen can cause polymer degradation.

Deciding if polymer is needed and what is target viscosity is done based on mobility ratio (FANCHI, 2010). Mobility ratio is calculated as ratio between oil mobility and water mobility as shown in equation 1.

$$M = \frac{\lambda_o}{\lambda_w} = \frac{\mu_o/k_o}{\mu_w/k_w}$$

Where: λ_{o-w} is oil / water mobility

μ_{o-w} is oil / water viscosity

k_{o-w} is oil / water relative permeability

equation 1.

Ideal case is that M=1 or slightly below, in that case uniform injection front can achieved without viscous fingers breaking through, as it is shown on figure 1. Example of polymer target viscosity calculation is shown in equation 2. Where water viscosity is changed with desired polymer viscosity.

$$\mu_{poly} = \frac{\mu_o \cdot k_w}{k_o \cdot M}$$

example: μ_o = 0,769 cP k_o = 124,42 mD

k_w = 349,83 mD M = 1

Target viscosity: μ_{poly} = 2,16 cP

equation 2.

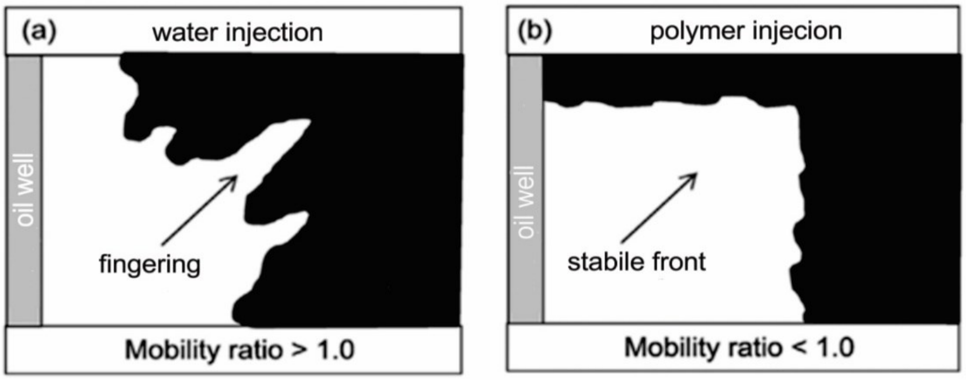

Figure 1 injection front shape (look from above) a) M>1, injection front breaking through forming viscous "fingers" b) M<1 stabile injection front achieved

When selecting polymer, the goal is to get sufficient viscosity with low concentration. Viscosity is influenced by mixing water salinity and by molecular mass of polymer itself (figure 2). The difference in viscosity for the same polymer mixed in formation water and technical water is very high. That's why, in terms of cost, it is always better if technical water is available. Polymers with higher molecular mass are creating higher viscosity solution for same concentration than ones with lower molecular mass but higher molecular mass means also higher polymer retention and higher injection resistivities so this also must be taken into account during polymer selection process.

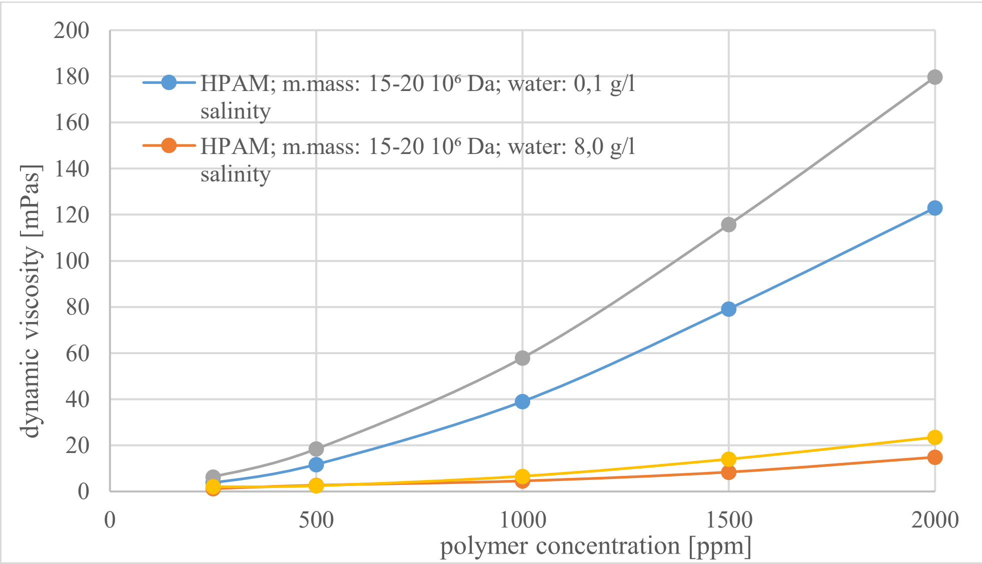

Figure 2 Concentration / viscosity dependence for 2 HPAM polymers with different molecular mass prepared with water with 2 different salinities

Polymer must be stable in time so long-term stability test has to be performed to check if polymer solution will keep desired viscosity in longer period (>30 days). It is good to prepare polymer solution with chosen mixing water, if formation water is used it probably has residual of chemicals used in oil preparation process that can influence mixture. If polymer is stabile in time, polymer selection is confirmed.

2.2 Polymer retention

After the polymer is confirmed, it is necessary to determine technical parameters needed for operation planning: Rf, Rm and RRF. The polymer retention factor (Rf) and parameters that derive form it – resistance modification (Rm) and residual resistance factor (RRF) are calculated from core flood experiment on actual or model reservoir rock, depending on availability. Resistance modification (Rm) is a ration between injection pressure for water and for polymer at same flow rate (FERREIRA & MORENO, 2018). It is calculated from differential pressure during water injection prior to polymer and differential pressure during polymer injection at same flow rate using following formula.

$$Rm = \frac{\Delta P_p}{\Delta P_w{}^{\text{before}}}$$	Where:	ΔP_p	Pressure during polymer injection	equation 3.
		$\Delta P_w{}^{\text{before}}$	Pressure during water injection before polymer	

Residual resistance factor (RFF) is ration between water injection pressure before and after polymer (FERREIRA & MORENO, 2018; THOMAS, A., 2019). It is calculated from differential pressure during water injection before and after polymer is injected through the sample using following formula:

$$RRF = \frac{\Delta P_w{}^{\text{after}}}{\Delta P_w{}^{\text{before}}}$$	Where:	$\Delta P_w{}^{\text{after}}$	Pressure during water injection after polymer	equation 4.
		$\Delta P_w{}^{\text{before}}$	Pressure during water injection before polymer	

Both parameters are important for planning field operations, Rm for assessment of injection pressure and RRF to assess injectivity of water after polymer, since in practice water is used in the final stage of cEOR as displacement fluid. Both parameters depend on polymer retention, measurement of polymer loss in formation. Adsorption on the surfaces, mechanical entrapment brought on by small passageways in porous media, and hydrodynamic entrapment brought on by high flow rates are the three main causes of polymer retention. The retained polymer lowers the porous media's flow capacity (permeability) by decreasing the flow area. Polymer retention is calculated from data obtained during coreflood test using concentration profile method (AL-HAJRI et al., 2018; SERIGHT, 2016; SORBIE, 2013; THOMAS, A,2019). To do that, polymer is prepared with addition of easy migrating tracer (i.e. solution of KI – potassium iodide). During the first polymer injection on the outlet of core holder tracer appears first and polymer after, that "lag" in polymer appearance is caused by polymer retention. After the first polymer injection, polymer is flushed by long water injection (50-100 pore volumes) or until stabile differential pressure is achieved. The polymer is again injected after flushing. This time polymer is appearing before tracer at the outlet because first to appear at the outlet is the polymer that was retained in pores during first polymer injection. Polymer retention is the difference between polymer appearance first and second polymer appearance in relation to tracer, expressed as mass of polymer per pass of rock. Theoretical curve of tracer and polymer concentration are shown on figure 3.

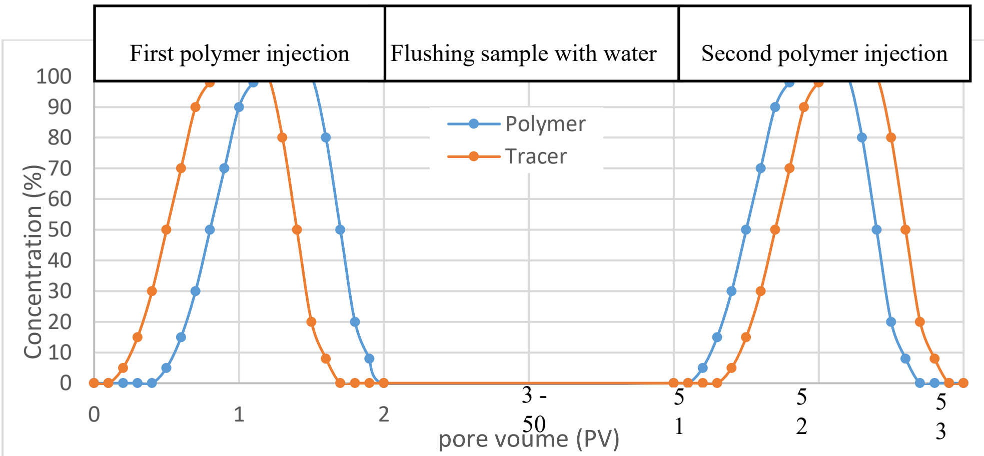

Figure 3 Theoretical curve of tracer and polymer concentration during coreflood test for Rf determination

The concentration of polymer on coreholder outlet during experiment was measured via in-line capillary tube and concentration of tracer was measured from changes in conductivity on the fluid caught at the outlet of coreholder. Method of retention calculation using polymer concentration profile is shown on figure 4 (SAMEER et al., 2018; ILYASOV et al., 2021). Polymer concentration curves for both injection curves are plotted on the same graph, tracer curves should overlap exactly because migration of tracer should be the same. Retention as volume of polymer is calculated as difference between points when polymer is reaching 50% of maximum concentration for first and second polymer injection.

$$R_{(PV)} = PV^{50\%}_{poly1} - PV^{50\%}_{poly2} \qquad \text{equation 5.}$$

From retention expressed as part of pore volume it is possible to calculate retention factor (Rf) using equation 6.

$$Rf = \frac{R_{(PV)} \times PV \times C}{m} \qquad \text{equation 6.}$$

Where:

$R_{(PV)}$	Retention as pore volume
PV	Pore volume (ml)
C	Polymer concentration (ppm)
m	Mass of the rock sample (g)

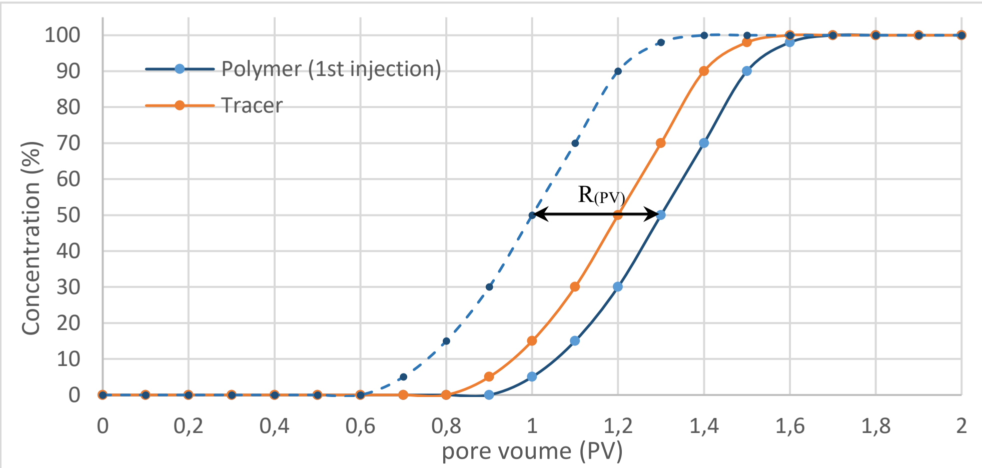

Figure 4 Overlapped curves for Polymer and Tracer concentration for first and second injection - Rf determination using concentration profile method

In case of unsatisfactory results, in terms of resistance modification (Rm), residual resistance factor (RRF) and polymer retention factor (Rf) process of polymer selection is repeated.

2.3 Surfactant selection and testing

Surfactants are surface-active substances with polar (or hydrophilic) head and a nonpolar (hydrophobic) tail, this allows them to have affinity to aqueous and non-aqueous phase due to the amphiphilic nature. All surfactant types can reduce the IFT between the aqueous and oil phase and change environment wettability to more water-wet conditions, but selecting the suitable type of surfactant is very crucial in terms of solubility, thermal and chemical stability, and adsorption of the surfactant under harsh reservoir conditions (BORCHARDt et al., 1985; EFTEKHARI et al., 2015). Generally, surfactants are classified into four main groups: non-ionic anionic, cationic, and zwitterionic or gemini (also known as amphoteric) (GUPTA et al., 2020; MAHBOOB et al., 2022; BERA & MANDAL, 2015; ISAAC et al., 2022). Most commercial surfactants are blend of two or more different types of surfactants regarding type of polar head to decrease adsorption and increase surfactant performance.

The first thing to consider when selecting the surfactant is compatibility with mixing water, it should not form any precipitates or cloudiness / turbidity when solution is prepared. This is important because turbidity of surfactant / water solution can interfere with interphase tension measurement – main parameter for surfactant selection. Interphase or interfacial tension (IFT) is observed on the border between two immiscible liquids that form a surface that behaves like an elastic membrane. IFT is a measure of force needed to change the surface of this “membrane”, unit of measurement is mN/m.

Oil / water tension is dependent on oil and water composition, and it can range from 10 to 30 mN/m. To successfully mobilize trapped oil held in small pores by capillary forces it is necessary to lower interphase tension to a point of forming microemulsion, weather it is Windsor type I microemulsion (oil dispersed in water phase) or Windsor type III microemulsion (microemulsion is separate phase between oil and water). It depends on the oil type, but it is usually achieved when IFT is lowered down to 10-2 – 10-3 mN/m range.

The Surfactant selection process consists of IFT measurement for different surfactant concentrations. If possible, prepare surfactant solution with chosen mixing water. If formation water is used it probably has residual chemicals used in oil preparation process that increase IFT, such as water clarifiers, or can influence surfactant performance. The goal is to determine the minimum achievable IFT value and critical micellar concentration (CMC). CMC is surfactant concentration at which lowest value of IFT is obtained, any increase inf surfactant concentration leading to micelle forming with little or no decrease inf IFT or even mild increase. Typical surfactant selection measurements are shown in figure 5: IFT dependence on concentration for four different surfactants with illustration of how surfactant behaves in solution. Most desirable characteristics for cEOR are observed with surfactant 2, very low IFT values and observed and mild decrease after reaching CMC.

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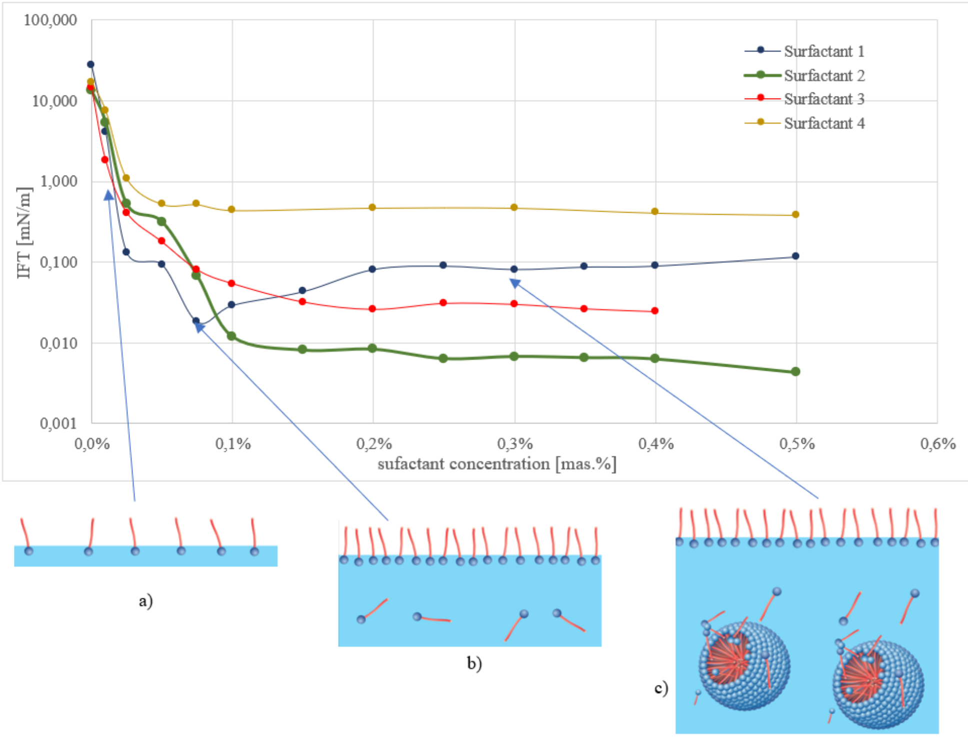


Figure 5 results of IFT measurements for 4 different surfactants, surfactant 2 shows the best characteristics for cEOR. Three different trends are visible on the graph: a) molecules of surfactant are positioning themselves on border between phases, with concentration increase IFT is decreasing b) border between phases is saturated with surfactant, CMC achieved, in most cases this is lowest IFT value c) since border is saturated any increase of surfactant leads to forming of spherical surfactant aggregates – micelle, little or no decrease of IFT, sometimes even increase inf IFT.

Additional benefit that derives from surfactant reaction with reservoir is changing reservoir rock wettability from oil wet to water wet (RATANPARA and KIM, 2023). Changing rock wettability can increase effects of cEOR with oil wet reservoirs (carbonate rich sandstones or limestones) but it is depending on surfactant adsorption on rock surface. Wettability change is important factor for increasing oil recovery since goal is to decrease capillary forces that are trapping the oil in small pores as it is shown by equation for capillary number (equation 7.). Capillary number (Ca) is ratio between viscous forces and capillary forces (GUO, SONG and HILFER, 2020). Higher the capillary number bigger the oil recovery, at Ca values in range 10^{-6} - 10^{-5} mobilization of trapped oil begins and values in range 10^{-3} -10^{-2} marks end of residual oil mobilization. If it is possible to decrease IFT and increase wetting angle at the same time capillary pressure will be lowered even more. Surfactants can change wettability of rock by means of adsorption on rock surface (anionic surfactants) (SUGIHARDJO, 2022) but adsorption is not desirable because it is taking surfactant out of solution. Wettability alteration is more often achieved by smart water injection - water injection with magnesium and sulphate ions (Mg^{+2}, SO_4^{-1}) such as seawater (AHMADI et al., 2020; POPIC et al., 2022).

cEOR projects that include reservoir rock wettability alteration were not done in Serbia so far and this segment will not be discussed in detail any further.

$$Ca = \frac{\nu \times \mu}{\sigma \times \cos\Theta} \qquad \text{equation 7.}$$

Where:

Ca	Capillary number [dimensionless]
ν	Darcy velocity [m/s]
μ	Viscosity of displacing phase [Pa·s]
γ	Interphase tension IFT [N/m]
Θ	Wetting angle of liquid

After surfactant selection it is recommended to perform compatibility test with polymer, if polymer is going to be used in cEOR. It is possible that some surfactants can decrease polymer viscosity when added to mixture. Same like with polymer and surfactant, preferably prepare surfactant polymer solution (SP) with chosen mixing water. It is done as form of thermostability test, surfactant polymer mixture is prepared and kept on reservoir temperature for 3 days. Each day viscosity is measured to determine if polymer degradation occurred. It is recommended to do this with various concentration of surfactant. Results with one such test were shown on figure 6 where it is visible that, in case surfactant and polymer are not compatible, polymer degradation is happening within 24 hours after preparation.

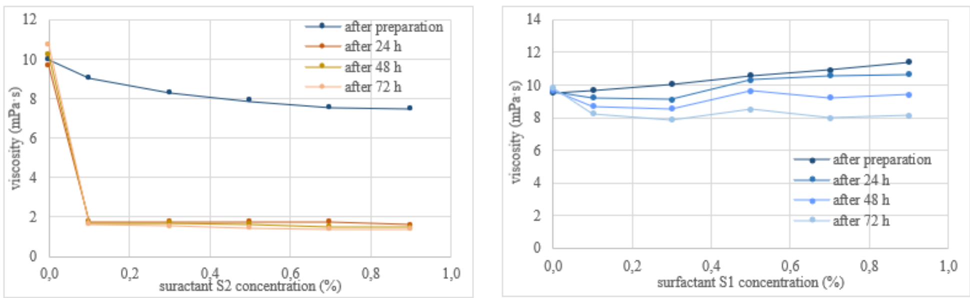


Figure 6 Example of compatibility test with incompatible (left) and compatible (right) SP mixture

In case of unsatisfactory results, in terms of polymer – surfactant compatibility process of surfactant or polymer surfactant selection is repeated.

2.4 Surfactant adsorption test

Surfactant adsorption is a measure of how much surfactant stays trapped on rock particles during injection (GROENENDIJK and VAN WUNNIK, 2021). This value can be significant and impact EOR process at first stages, however adsorption is active until equilibrium is reached between rock and injected solution. In the latter stage, when water is injected to push SP or ASP solution, desorption process will be activated because injected fluid doesn't contain surfactant, and all surfactants will be flushed from rock surface. In this way, the adsorption process acts like surfactant "retarder" since surfactant is not permanently trapped as it is case with polymer. Surfactant adsorption can be measured with static adsorption test or dynamic adsorption test (AL-MURAYRI et al., 2019). Static tests are simpler, and dynamic is more accurate.

Static test is performed by soaking the rock sample in surfactant solution of known concentration for minimum of one week at reservoir temperature (long time is needed since diffusion is only mechanism for surfactant transfer within sample). After soaking time fluid is drained from sample and average concentration of surfactant measured in recovered fluid. Adsorption is calculated through material balance, decrease in mass of surfactant in ratio to mass of rock sample, mg or μg of surfactant per g of rock sample – in units mg/g or μg/g. Surfactant concentration can be measured by High-performance liquid chromatography (HPLC) – direct measurement, changes in IFT measured by spinning drop tensiometer – indirect measurement or Fourier-transform infrared spectroscopy (FTIR) – indirect measurement.

Dynamic adsorption test is performed on similar principle as polymer retention test, using concentration profile. The core sample is saturated with 2% NaCl solution, after saturation phase surfactant mixed in 3% NaCl solution is injected in the core, at least 5 pore volumes to make sure that saturation is reached – adsorption phase. After surfactant solution is injected sample is flushed with 5 pore volumes of 2% NaCl solution – desorption phase. Changes in salinity (NaCl concentration) is used as inert tracer, and it can be measured by changes in conductivity of fluid at outlet. Surfactant concentration at the outlet is monitored by periodical sampling and detection by one of the methods mentioned for static method. The same test can be repeated with surfactant + polymer mixture used, instead of just surfactant – in case that polymer is used in cEOR. Surfactant adsorption is lower in SP mixture (due to polymer retention) in comparing with pure surfactant solution so if both tests are done, we can get clearer information on expected range of surfactant adsorption in reservoir. Theoretical curves of dynamic adsorption test are shown in figure 7.

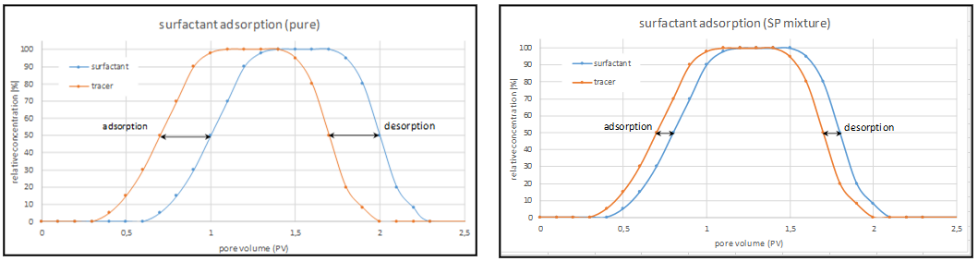


Figure 7 Example of theoretical concentration curves of dynamic adsorption test

Adsorption / desorption is calculated using concentration profile method, with difference in volume at 50% concentration for surfactant and tracer, already described in detail for polymer retention.

Generally, surfactant adsorption is higher than polymer, mainly ionic surfactants, it is also depending on rock surface so higher clay / fines content means more adsorption. In case of unsatisfactory results, if surfactant adsorption is too high the process of surfactant selection is repeated or adding alkali or other "sacrificial" surfactant is considered. Sacrificial surfactants have a role to be adsorbed onto rock surface instead of main one.

2.5 Alkali selection and testing

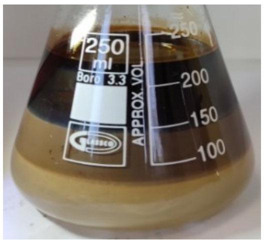
Basic function of alkali in cEOR is to form surfactant in contact with naphthenic acids that will additionally mobilize trapped oil. This is useful in reservoirs with long distances between injection and production well, to avoid surfactant adsorption to rock before it reaches areas with trapped oil. Condition that alkali can be used in this way is dependent of total acid number (TAN) of oil (measure of how many mg of potassium hydroxide – KOH is needed to neutralize organic acids in 1g of oil). If TAN is above 0,5-0,8 mg KOH/g there is potential of forming sufficient quantities of surfactant. The secondary function of alkali is to decrease adsorption of surfactant (anionic mainly) as "sacrificial" agents – alkali is adsorbed to rock surface instead of surfactant (HAZARIKA and GOGOI, 2019). Most widely used is sodium carbonate (Na2CO3) or, if there is risk of carbonate scale precipitation, monoethanol amine (MEA - C2H7NO). The concentration that is used is usually 1% solution, but it depends on mixing water and surfactant in use, it is necessary for injection mixture to have pH of 8,0-8,5 to form surfactants with naphthenic acids.

When it is put in perspective of local condition, in Serbian oilfields, there is much potential for alkali application on cEOR. TAN measured on oilfields on Serbia varies from 0,03 to 5,16 mg KOH/g so there is potential for use, but lot of commercially available surfactants have pH above 8 so there is no need to add alkali. Major oilfields in Serbia with potential for cEOR are well covered with network of wells so distance between injection and production well is not that big and sweep area can be covered with surfactant without excessive loss. The only potential use is to decrease adsorption of surfactants if it is proven to be too high.

One of biggest disadvantages of alkali use is quantity needed, since concentration of alkali needed is highest comparing to other components in cEOR, surfactant and polymer (in example: alkali concentration of 1%, surfactant 0,3% and polymer 0,1% - real ratio on the ASP flooding project). The biggest logistic challenge is to supply and stock enough alkali, since quantity needed is higher than quantity of surfactant and polymer together and if used it is increasing cost of entire operation.

2.6 Emulsion forming test / bottle test

The bottle test is a fundamental and traditional surfactant selection method. It is carried out to evaluate and compare the quantity, stability, and capacity to form microemulsions. Bottle tests are conducted using reservoir oil that is extracted from the produced fluid purely by heating it without the use of chemicals. A surfactant or an alkali/surfactant mixture made with model or, preferably, real mixing water is used for preparation. Oil and alkali surfactant / surfactant solution were mixed in 1:1 ratio. After turning the bottle upside down continuously by hand for 2 minutes, samples are placed into a thermo regulated oven at formation temperature for a period of 30 days. Samples were removed once daily to determine the type, quantity, and presence of microemulsion. It is widely believed that in surfactant selection process one of the main criteria is type of microemulsion formed with oil and its stability (BERA & MANDAL, 2015; GUO et al., 2012; SALAGER et al., 2013) – Windsor type III microemulsion that is stabile in time at reservoir condition (figure 8).



oil 75 ml, microemulsion 55 ml, water phase 90 ml

oil 30 ml, microemulsion 80 ml, water phase 80 ml

Figure 8 Example of bottle test samples with Windsor type III microemulsion (interphase in the middle)

General criteria are that, when comparing two surfactants, one that has more Windsor type III microemulsion that is more stable in time will perform better in cEOR but in our experience it is not determining factor – some of surfactants that had good results in bottle test didn't perform well in coreflood test and vice versa. Most useful information that can be obtained is viscosity of formed microemulsion. It is possible that microemulsion that is formed has very high viscosity and that it is practically immobile in reservoir conditions. It can lead to reservoir plugging, injectivity issues and many other problems.

For that matter this test can be modified in terms of observation period. Tests are set in same way and as soon as sufficient quantity of microemulsion is formed it can be sampled and viscosity measurement performed at reservoir conditions. It can be surfactant or alkali surfactant exclusion criteria for cEOR implementation – if viscosity of formed microemulsion is too high it cannot be used in cEOR.

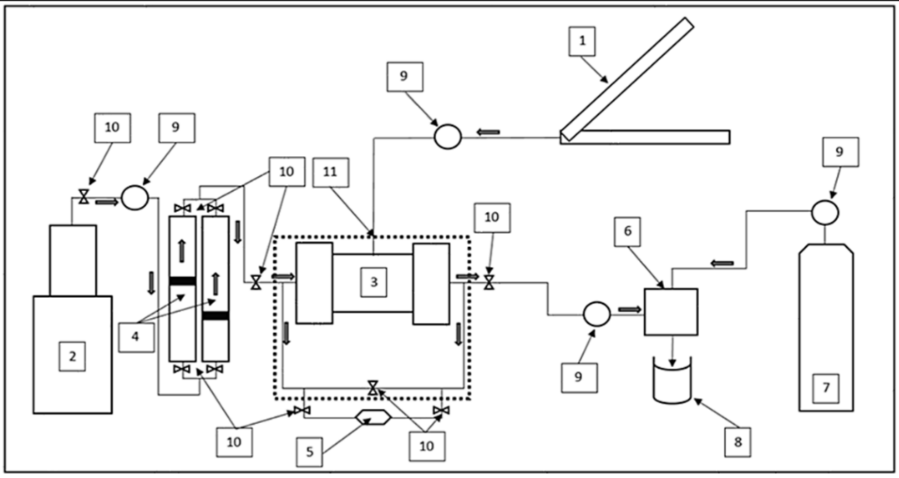
2.7 Salinity test

Salinity influences phase solubility of surfactants, only ionic and amphoteric (zwitterionic or gemini) surfactants, non-ionic surfactants are not influenced. At higher salinity surfactants are highly oil soluble and on lower salinity it is highly water soluble, with amphoteric surfactant this also dependents on pH of solution (HAJIYEV et al., 2023). At optimum salinity surfactant is equally soluble in water and oil and in this way lowest IFT is obtained. This is also influencing microemulsion Windsor type III stability since at optimum salinity IFT at oil-microemulsion and microemulsion water contacts are equal ($\sigma om = \sigma mw$).

As mentioned before, most of the commercial surfactants are blend of two or more different surfactant types so salinity test efficiency depends on selected surfactant blend. It is done when surfactant is already selected and IFT measurements are repeated with selected surfactant at selected concentration with addition of salt (NaCl) in solution in different concentrations. If there is trend of decreasing IFT then optimum salinity is determined though repeated testing, if not – salinity of mixing water is higher than optimum salinity for given surfactant. At projects that were done for Serbian oilfields salinity scan was done but no change in IFT was detected or influence on microemulsion stability was observed so this segment will not be discussed in detail any further.

2.8 Oil recovery coreflood test

Most reliable way to test ability of surfactant or ASP / SP mixtures to mobilize residual oil from porous rock is to perform coreflood tests on rock sample, preferably cut or consolidated (in case of loose or poorly cemented sandstone) from core cut during drilling of oil wells. As criteria to determine selected mixture performance changes in oil recovery factor (ORF) should be used. ORF represents a decrease in residual oil saturation (Soi-Sor) divided by initial oil saturation (Soi). All rock samples must undergo soxhlet extraction using toluene to remove any residual oil or contamination. The test should be done at reservoir temperature and with pressures (pore pressure, overburden pressure) as close to reservoir conditions as possible. As for fluids: reservoir oil extracted from produced fluid only by heating without chemicals should be used, oil should be diluted with petroleum benzine (C7 n and iso alkanes with cyclic HC) to get viscosity at reservoir conditions, modelled formation water should be used as water phase and SP / ASP mixture should be prepared with actual water that will be used during operation. Setup of coreflood system with all necessary elements to perform oil recovery test is shown on figure 9.



1.Hand pump for Overburden (OB) pressure 2.Injection pump
3.Core Holder 4.Floating piston accumulators
5.Differential pressure sensors 6.Back pressure regulator (BPR)
7.Bottle of nitrogen for BPR 8.Fluid collector
9.Manometers 10.Valves
11.Oven

Figure 9 recommended setup of coreflood system

Coreflood experiment was done in as per following steps:

- Injecting the model formation water (MFW) at three flow rates until the differential pressure stabilizes (minimum 1 pore volume), goal is to determine linear permeability for MFW (Kw).

- Injection of oil at a constant flow rate until the differential pressure stabilizes (minimum 3 pore volumes). Fluid at the outlet is sampled and initial water saturation (Swi) is determined by measuring quantity of produced fluid.

- Partial isolation of the core sample on reservoir conditions (aging process) for a period of 72 h. Oil is periodically injected for six hours at the lowest possible flow rate.

- Oil injection at three flow rates until the differential pressure stabilizes (minimum 1 pore volume). Linear effective permeability for oil (Ko@Swi) is determined.

- Injecting MFW at constant flow rate until the differential pressure stabilizes (minimum 3 pore volumes) – pre-flush phase. During injection, fluid at the outlet is continuously sampled, the volume of displaced oil is monitored to determine change in oil recovery factor (ORF1). After stabilizing the differential pressure, the effective permeability for MFW (Kw1@Sor) is determined. 2-3 pore volumes of MFW re injected at an increased flow rate to confirm ORF value. The goal of this stage is to imitate water injection and to remove oil that that ca be produced this way. In this way any additional quantities of oil are produced are result of cEOR.

- Injecting selected ASP / SP mixture or mixtures, amount should correspond to volume planned for field application (usually 0,2-0,5 pore volume) – main treatment phase. Differential pressure should be recorded and the fluid at the outlet is continuously sampled (every 0.2 pore volume). Volume of displaced oil is monitored to determine change in oil recovery factor (ORF2). The goal of this stage is to imitate as accurately as possible planned cEOR operations in the field.

- Injecting MFW at constant flow rate. The MFW is pressed until the differential pressure stabilizes (minimum 3 pore volumes) – post-flush phase. During indentation, the fluid at the outlet is continuously sampled every 0.5 pore volume. Volume of displaced oil is monitored to determine change in oil recovery factor (ORF3). After differential pressure is stabilized, the effective permeability for MFW (Kw2@Sor) is determined. The goal of this stage is to imitate the final cEOR operation when injected chemicals are pushed by water injection.

Examples of this kind of test are shown in figure 10. The results of this test give the most accurate assessment of additional oil that can be produced for cEOR methods. The heterogeneity of reservoir must be taken into account so preferably more than one test should be done with samples of different permeability. From this experiment it is also possible to calculate resistance modification (Rm) and residual resistance factor (RRF), in same way as it's done in polymer retention test, only difference that results calculated from oil recovery coreflood test are more accurate because residual oil is present in system as it would be in reservoir conditions.

Additional quantities of oil that can be gained are calculated as difference in residual oil saturation (or ORF) after pre-flush and post-flush phase. Satisfactory results are one that indicate that increase in oil production will justify investing in implementation of cEOR methods and it depends on many factors, not just reservoir conditions. This is the main test to assess if selected chemicals can be used. In case of unsatisfactory results in terms of oil recovery or Rm and RRF, surfactant and / or polymer cannot be used in cEOR and selection process is repeated.

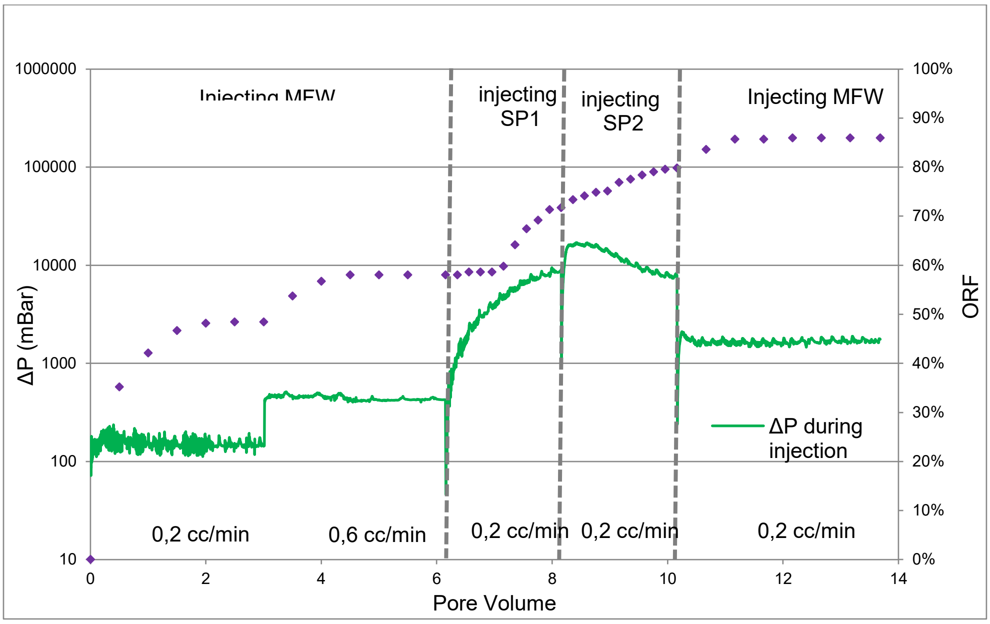


Figure 10 Changes in differential pressure and ORF during injection of SP mixtures. SP1 – mixture prepared with 0,1% surfactant concentration, SP2 – mixture prepared with 0,5% surfactant concentration. Polymer concentration in both cases is the same

3 RECOMMENDED WORKFLOW ALGORITHM

All mentioned tests are important for final decision if certain polymer or surfactant can be used in cEOR but some of tests are longer, more complex and more expensive than others. Our goal was to organize testing procedures in a way that will allow us to do preliminary selection with cheaper and faster tests and to perform more complex and more expensive tests on products that have already passed the first screening methods. The algorithm is shown in figure 11. Our goal was to create universally applicable workflow, regardless of what components of cEOR are used.

Before any laboratory tests it is necessary to select water that will be used for injection. Type of water (formation water or technical), available quantities and quality of water play major role in chemical selection, polymer especially, and even can influence financial aspects of EOR project itself. Selection of polymer and surfactant is done simultaneously, polymer according to target mobility and surfactant according to optimal IFT to concentration ratio.

Next step is to check for surfactant and polymer compatibility at reservoir temperature, followed by bottle test and salinity scan – to check for microemulsion forming and stability. On this step we can consider introducing alkali in mixture, to aid microemulsion stability.

With defined SP/ASP mixture, coreflood tests are performed to assess decrease of oil saturation, retention of polymer and adsorption of surfactant. The methodology of all coreflood tests is designed in the way to deliver maximum information with available equipment. If surfactant adsorption is too high, we consider introducing co-solvent or alkali in mixture.

In organizing process in this way, we can do most of necessary preparation for field test in 6-month period.

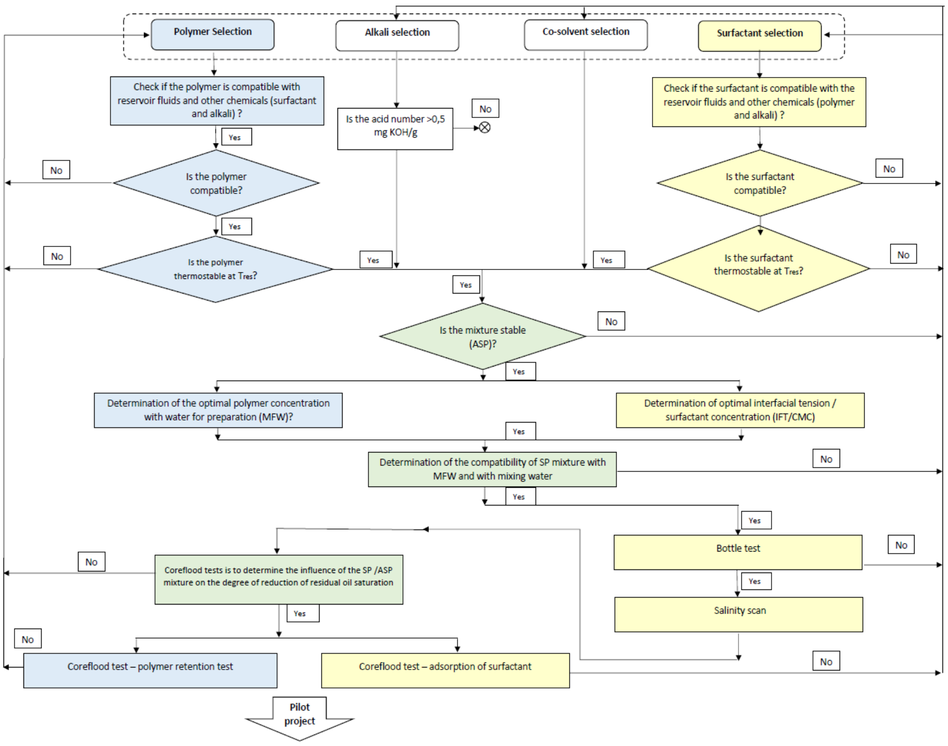


Figure 11 Recommended workflow algorithm for process of chemical components selection for EOR

4 CONCLUSION

When chemical selection process for cEOR is analyzed with respect to local condition we can separate some key points specific to Serbian oilfields.

- Absence of secondary production methods (water injection) and related infrastructure (water treatment units, pipelines, etc.) is putting additional costs on any plan to implement any cEOR method. Because of that, an additional quantity of oil produced by cEOR must be sufficient to justify investing in cEOR.

- Surfactant / polymer compatibility issues are one of biggest problems and this test should be done as soon as possible to avoid unnecessary testing of chemicals.

- Total acid number values of oil in Serbian oilfields are high enough to suggest that alkali should be used but since all major oilfields are evenly covered with production wells there is no need for use of alkali, except as an agent for surfactant adsorption.

- Final and decisive test if selected cEOR mixture will be able to mobilize trapped oil should be done with oil recovery coreflood test done on real rock sample from reservoir. In this way it is possible to imitate injected fluid-oil-rock interaction that takes place in the reservoir and to give clear indication if selected cEOR method is applicable or not.

In current situation, it is important for oil industry in Serbia to move in direction of increasing oil recovery from oilfields that are already in production for some time by chemical or any other EOR method. Developing technical skills and methods to realize this kind of project is one of biggest challenges for our company. All other challenges are available on STC website: Tehnološki izazovi - Naučno-tehnološki centar NIS-Naftagas.

REFERENCES

AHMADI, S. et al. (2020) 'Wettability alteration and oil recovery by spontaneous imbibition of smart water and surfactants into carbonates,' Petroleum Science, 17(3), pp. 712–721. https://doi.org/10.1007/s12182-019-00412-1

AL-HAJRI, S. et al. (2018) ' An overview on polymer retention in porous media,' Energies, 11(10), p. 2751. https://doi.org/10.3390/en11102751

AL-MURAYRI, M.T. et al. (2019) Alkali-Surfactant Adsorption and Polymer Injectivity Measurements Using Reservoir Core from a Giant High Temperature and High Salinity Clastic Reservoir to Design an ASP Pilot. https://doi.org/10.2118/198174-ms

BERA, A. and MANDAL, A. (2014) 'Microemulsions: a novel approach to enhanced oil recovery: a review,' Journal of Petroleum Exploration and Production Technology, 5(3), pp. 255–268. https://doi.org/10.1007/s13202-014-0139-5

BORCHARDT, J.K. et al. (1985) 'Surfactants for CO_2 foam flooding,' All Days [Preprint]. https://doi.org/10.2118/14394-ms

EFTEKHARI, A.A., KRASTEV, R. and FARAJZADEH, R. (2015) 'Foam stabilized by fly ash nanoparticles for enhancing oil recovery,' Industrial & Engineering Chemistry Research, 54(50), pp. 12482–12491. https://doi.org/10.1021/acs.iecr.5b03955

FANCHI, J. (2010) Integrated Reservoir Asset Management: Principles and Best Practices. Gulf Professional Publishing

FERREIRA, V.H.S. and MORENo, R.B.Z.L. (2019) 'Rheology-based method for calculating polymer inaccessible pore volume in core flooding experiments,' E3S Web of Conferences, 89, p. 04001. https://doi.org/10.1051/e3sconf/20198904001

GROENENDIJK, D.J. and VAN WUNNIK, J.N.M. (2021) 'The impact of micelle formation on surfactant Adsorption–Desorption,' ACS Omega, 6(3), pp. 2248–2254. https://doi.org/10.1021/acsomega.0c05532

GUO, H., SONG, K. and HILFER, R. (2020) 'A Critical Review of Capillary Number and its Application in Enhanced Oil Recovery,' SPE Improved Oil Recovery Conference [Preprint]. https://doi.org/10.2118/200419-ms

GUO, Y.-J. et al. (2012) 'Solution property investigation of combination flooding systems consisting of Gemini–Non-ionic mixed surfactant and hydrophobically associating polyacrylamide for enhanced oil recovery,' Energy & Fuels, 26(4), pp. 2116–2123. https://doi.org/10.1021/ef202005p

GUPTA, I., RAI, C.S. and SONDERGELD, C.H. (2020) 'Impact of surfactants on hydrocarbon mobility in shales,' SPE Reservoir Evaluation & Engineering, 23(03), pp. 1105–1117. https://doi.org/10.2118/201110-pa

HAJIYEV, M. et al. (2023) ' Revisiting the effect of oil type and pressure on optimum salinity of EOR surfactant formulation using phase behavior evaluation,' Geoenergy Science and Engineering, 230, p. 212259. https://doi.org/10.1016/j.geoen.2023.212259

HAZARIKA, K. and GOGOI, S.B. (2019) 'Effect of alkali on alkali–surfactant flooding in an Upper Assam oil field,' Journal of Petroleum Exploration and Production Technology, 10(4), pp. 1591–1601. https://doi.org/10.1007/s13202-019-00794-3

ILYASOV, I. et al. (2021) 'Polymer retention determination in porous media for polymer flooding in unconsolidated reservoir,' Polymers, 13(16), p. 2737. https://doi.org/10.3390/polym13162737

ISAAC, O.T. et al. (2022) 'Surfactants employed in conventional and unconventional reservoirs for enhanced oil recovery—A review,' Energy Reports, 8, pp. 2806–2830. https://doi.org/10.1016/j.egyr.2022.01.187

JOUENNE, S., KLIMENKO, A. and LEVITT, D. (2016) 'Polymer flooding: establishing specifications for dissolved oxygen and iron in injection water,' SPE Journal, 22(02), pp. 438–446. https://doi.org/10.2118/179614-pa

POPIC, D. et al. (2022) 'Influence of reservoir mineralogy on oil recovery during polymer flooding,' Neftyanoe Khozyaystvo - Oil Industry, (4), pp. 44–48. https://doi.org/10.24887/0028-2448-2022-4-44-48

RATANPARA, A. and KIM, M. (2023) 'Wettability Alteration Mechanisms in Enhanced Oil Recovery with Surfactants and Nanofluids: A Review with Microfluidic Applications,' Energies, 16(24), p. 8003. https://doi.org/10.3390/en16248003

SALAGER, J., FORGIARINI, A.M. and BULLÓN, J. (2013) 'How to Attain Ultralow Interfacial Tension and Three-Phase Behavior with Surfactant Formulation for Enhanced Oil Recovery: A Review. Part 1. Optimum Formulation for Simple Surfactant–Oil–Water Ternary Systems,' Journal of Surfactants and Detergents, 16(4), pp. 449–472. https://doi.org/10.1007/s11743-013-1470-4

SERIGHT, R.S. (2016) 'How much polymer should be injected during a polymer flood? Review of previous and current practices,' SPE Journal, 22(01), pp. 1–18. https://doi.org/10.2118/179543-pa

SERIGHT, R.S. S. and SKJEVRAK, I. (2015) 'Effect of dissolved iron and oxygen on stability of hydrolyzed polyacrylamide polymers,' SPE Journal, 20(03), pp. 433–441. https://doi.org/10.2118/169030-pa

SHUTANG, G., HUABIN, L. and HONGFU, L. (1995) 'Laboratory investigation of combination of Alkali/Surfactant/Polymer technology for Daqing EOR,' SPE Reservoir Engineering, 10(03), pp. 194–197. https://doi.org/10.2118/27631-pa

SORBIE, K.S. (2013) Polymer-Improved oil recovery. Springer Science & Business Media

SUGIHARDJO, S. (2022) 'Surfactant-Induced wettability alteration,' Scientific Contributions Oil and Gas, 32(1), pp. 56–63. https://doi.org/10.29017/scog.32.1.834

THOMAS, A. (2019) Essentials of polymer flooding technique. John Wiley & Sons.

WANG, J. et al. (2007) ' Understanding of the Fluid Flow Mechanism in Porous Media of EOR by ASP Flooding from Physical Modeling,' All Days [Preprint]. https://doi.org/10.2523/iptc-11257-ms

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Original scientific paper

PELLETIZATION OF FLY ASH FOR UTILIZATION IN DYNAMIC SORPTION PROCESSES

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Abstract: Fly ash, a byproduct of coal combustion in thermal power plants, has transitioned from industrial waste to a valuable technogenic raw material. Its alumino-silicate composition, porous structure, large specific surface area, and sorption activity make fly ash an efficient and low-cost sorbent for removing metal ions from acidic mine waters but only in discontinuous (static) systems. Its small particle size and poor hydraulic properties limit its application in continuous (dynamic) water treatment systems. This study aims to produce fly ash pellets with suitable properties for use as a sorbent in dynamic- column purification systems. By agglomerating fly ash with cement and plasticizer, pellets with enhanced mechanical properties such as compressive strength, impact strength, abrasion resistance, and disintegration time in water were developed. These pellets promise to improve the applicability and effectiveness of fly ash in dynamic water treatment processes, offering an economical and efficient solution for removing metal contaminants from wastewater.

Keywords: fly ash, sorbent, agglomeration, cement, plasticizer

1 INTRODUCTION

As economies continuously develop, people's living standards improve. However, this progress also heightens the demand for energy and other resources, resulting in environmental pollution issues like water and air contaminants. In today's world, there

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are numerous advanced technologies for wastewater treatment that effectively reduce pollutant levels to concentrations safe enough for discharge into watercourses or for recycling as technical water in the production process. Recently, significant attention has been focused on selecting and producing cost-effective sorbents with high metal-binding capacities.

Fly ash (FA), an industrial byproduct of coal combustion, consists of fine particles. The rapid pace of industrialization and the high demand for electricity have led to the annual discharge of hundreds of millions of tons of FA worldwide. While coal-fired power generation supplies energy for both daily life and industrial activities, it also contributes to air and water pollution, disrupting ecological cycles. If FA is released directly into the atmosphere from power plant chimneys without proper treatment, it pollutes the air and poses significant health risks to humans (Bartoňová, 2015).

As science and technology have advanced, FA from thermal power plants has transformed from an industrial waste product into a valuable raw material, known as technogenic raw material (Iyer and Scott, 2001; Zhuang et al., 2016; Park et al., 2014). The properties of FA largely depend on the type of coal used and the combustion conditions. Due to its alumino-silicate composition, porous structure, large specific surface area, and sorption activity, FA has emerged as an efficient and low-cost sorbent for the removal of metal ions from acidic mine waters (Alterary and Marei, 2021; Lanzerstorfer, 2018; YAO et al., 2015; Mohan and Gandhimathi, 2009; Bayat, 2002). However, the small particle size and poor hydraulic properties of FA pose challenges for its use in dynamic water treatment systems. Therefore, the aim of this study is to produce FA pellets with properties that are suitable for use as a sorbent in column purification systems. By transforming FA into pellets, the idea is to enhance its applicability and effectiveness in dynamic water treatment processes, thereby providing an economical and efficient solution for removing metal contaminants from wastewater.

2 FLY ASH PELLETS PREPARATION

The initial components for the preparation of pellets were FA, Portland cement, plasticizer, and water.

2.1 Fly ash characterization

Fly ash, the residue of the lignite combustion from the cyclones and electrostatic filters in the Nikola Tesla B Thermal Power Plant (TENT B), Obrenovac, Serbia was used.

Chemical composition of FA, shown in Table 1, indicates that the dominant components are silicon dioxide and aluminum oxide, with significant amounts of calcium and iron oxides.

Table 1 Chemical analysis of FA

Content (mass %)							
SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	K_2O	Na_2O	TiO_2
47.80	30.53	8.69	5.47	2.29	1.49	0.25	1.02
Cd	Pb	Zn	Cu	Cr	Ni	Mn	LOI
0.005	0.04	0.021	0.005	0.022	0.03	0.045	1.45

It can be concluded that the FA belongs to the Class F (according to the ASTM C618 standard), which indicates its pozzolanic properties and that some agents for improving binding characteristics (cement, plasticizer, lime) should be used in the pelletization process.

Mineralogical analysis showed that quartz is the main phase, while mullite and plagioclase are present in smaller quantities. Also, the amount of the amorphous phase is significant.

Particle size distribution, performed by laser light diffraction method using Helos (H1597) & Sucell R4, Sympatec GmbH, Figure 1, indicates that FA contains 40-80% of particles below 150 μm while their average size is 100 μm.

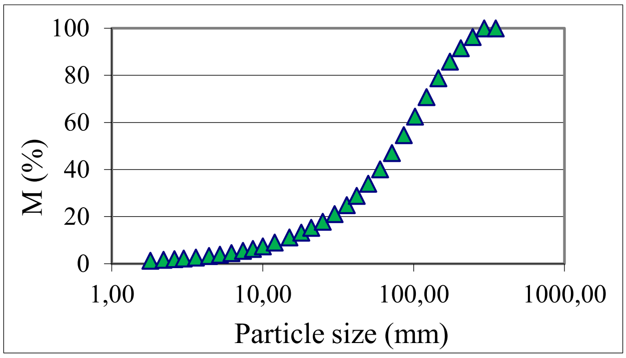

Figure 1 Particle size distribution of FA

The basic **physical properties** of FA were determined by the laser light scattering method, Table 2.

Table 2 Physical properties of FA

D_{10} (μm)	D_{50} (μm)	D_{90} (μm)	Specific surface area (cm^2/g)	ρ (g/cm^3)
13.33	77.43	197.23	4487.52	0.56

2.2 Cement characterization

The chemical composition, physical and mechanical properties of cement, used as a binder, according to the manufacturer's specification, are shown in Tables 3 and 4.

Table 3 Chemical analysis of Portland cement

Component/ content (%)							
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	P_2O_5
21.10	5.42	2.38	63.18	2.35	0.74	0.23	0.12
SO_3< 4 %	Cl	Na_2O_{eq}	ZnO	Mn_2O_3	SrO	TiO_2	
3.56	0.0386	0.72	0.038	0.11	0.099	0.245	

Table 4 Physical and mechanical properties of cement

Property	Value
Specific surface area of particles according to Blaine	4010 cm^2/g
Density	3.11 g/cm^3
R32	8.39 %
Initial setting time	130 min
Final setting time	160 min
Consistency	28.4 %
Expansion	0.5 mm
Compressive strength, after 2 days	35.5 MPa
Compressive strength, after 28 days	60.9 MPa
Flexural strength, after 2 days	6.7 MPa
Flexural strength, after 28 days	9.3 MPa

2.3 Plasticizer characterization

A highly efficient superplasticizer of the new generation (hyperplasticizer)- Cementol Hiperplast 463 (manufactured by TKK, Slovenia) was used as a chemical additive. The following advantages are listed in the technical data sheet of the product: high early and final strengths, improved water impermeability, slower carbonation, concreting at higher temperatures, durability, etc.

The characteristics of this superplasticizer are in accordance with the SIST EN 934-1 and SIST EN 934-2 standards and are given in Table 5.

Table 5 Physico-chemical properties of the used superplasticizer

Property	Declared values with permissible deviations
Appearance	brown yellow liquid
Density, 20°C	1.08 ± 0.02 kg/dm^3
Dry matter content	32.0 ± 1.6%
pH value	6.5 ± 1
Water soluble chlorides content	-
Alkali content (Na_2O equivalent)	< 3.0 %

The effect of this chemical additive depends on the type and amount of cement, the water-cement factor, the composition of the aggregate and the dosage of the superplasticizer itself.

The approximate dosage is between 0.2 and 1.5 kg per 100 kg of cement. It is used concentrated to the prepared fresh mixture or diluted with water, whereby it is optimal to use it after 70-80% of water has been added. The manufacturer recommends a mixing time of 3 min after adding the superplasticizer, with a minimum of 1 minute.

2.4 Pelletization procedure

During the pellets production, two series of mixtures were used, both composed of 90 % FA with 10 % cement, whereby the first one (FA+C+P) was moisturized by water with plasticizer and the second (FA+C) only by water.

Table 6 Components for pellets production

Series	Fly ash	Cement	Plasticizer	Water
FA+C+P	90 %	10 %	0.15 ml	275 ml
FA+C	90 %	10 %	-	300 ml

C-cement, P-plasticizer

Pelletization was performed in a pelletizer with disc dimensions of 40 cm diameter and 10 cm depth, an inclination of 50º and a speed of 15 rpm. Fly ash was mixed with cement as a binder. Tap water was added to the amount necessary for an optimal process and smooth operation of the pelletizer. The estimation of the required quantity of water is based on experience. In the case of plasticizer application, less water was added due to the steric effect of plasticizers based on polycarboxylate chains. The plasticizer acts by being gradually absorbed into the cement particles; polymer molecules cross-link the cement particles and prevent them from joining. Absorption takes place gradually and over a longer period.

Figure 2 shows the process of FA agglomeration in the pelletizing disc.

Figure 2 Pelletization of FA

After preparation in the pelletizer, the prepared "green" pellets were cured for three days in an atmosphere with 90% humidity; then they were dried in a laboratory drying oven and dry sieved using a vibro sieve into four size classes.

After each pelletization and sieving, the grain composition of the pellets was determined, which was within similar limits regardless of their composition. The adopted mean value of the granulometric composition is shown in Figure 3.

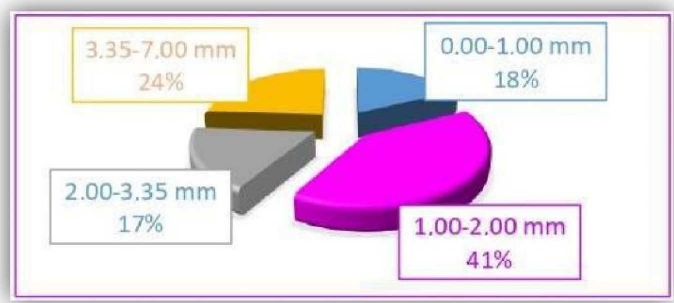

Figure 3 Average granulometric composition of pellets

Figure 4 shows a dominant presence (41 %) of the grain size class ranging from 1.0 to 2.0 mm, which is desirable considering that optimal batching of dynamic water purification systems requires particle sizes in the range of 1.0-5.0 mm. Also, it is obvious that the share of less desirable pellets for dynamic purification systems is below 20%.

3 MECHANICAL PROPERTIES OF THE PELLETS

The quality of the produced FA pellets was estimated by mechanical properties testing compressive strength, impact strength, abrasion resistance, and time of disintegration in water.

The resistance of pellets to compression, impact, and abrasion are properties crucial for transport and handling before their actual use. In the case of using pellets in dynamic purification systems (columns), it is necessary to know the time of pellets' disintegration in water to ensure that they do not break down during the column's operating cycle.

3.1 Compression or crush test

The compressive strength of pellets was tested on a set of 10 pellets using a standard hydraulic laboratory press (Tonindustrie, Germany) to determine the maximum pressure a pellet can withstand without breaking. The testing was conducted according to the procedure and recommendation that pellets should withstand a minimum of 0.5 kg/pellet, which enables secure further handling, suggested by the company Mars Mineral (Albert and Langford, 1998).

Table 7 presents the average values of the obtained compressive strength results for FA pellets by grain-size classes.

Table 7 Compressive strength of pellets by grain-size classes

	1.0-2.0 mm	2.0-3.35 mm	3.35-7.0 mm
		kg/pellet	
FA+C+P	0.45	0.60	1.12
FA+C	0.32	0.51	0.73

Based on the values shown in Table 7, it is noted that pellets exhibited satisfactory compression resistance, especially the coarser pellets. The maximum achieved compressive strength of the pellets for the 1.0-2.0 mm size class is just below the lower limit value of 0.5 kg/pellet, which can be considered satisfactory. For coarser size classes, the achieved compressive strength is significantly above the lower limit value. The ability of these pellets to withstand significant pressure without breaking suggests that they are robust enough for handling and use in water purification systems. This property is essential to ensure that the pellets do not disintegrate under the mechanical stress of operational conditions. The presence of plasticizer improves mechanical stability of the pellets.

3.2 Impact or drop test

The impact strength of pellets is tested by dropping a set of 10 pellets weighting 100 g in total, 25 times from a height of 457 mm onto a steel plate 9 mm thick. The sample is then sieved on a sieve of appropriate mesh size (depending on the grain size class being tested), and the mass of the undersize is weighted. The results are presented as a mass percentage with respect to the initial sample mass and should not exceed 5% (rarely 10%) of the total initial sample mass.

Table 8 presents the average values of the obtained impact strength results for FA pellets by grain-size classes.

Table 8 Impact strength of pellets by grain-size classes.

	1.0-2.0 mm	2.0-3.35 mm	3.35-7.0 mm
		%	
FA+C+P	10.5	9.3	9.2
FA+C	19.3	16.1	14.6

Based on the values shown in Table 8, it is noted that pellets with cement and plasticizer fully meet the standard criteria regarding impact resistance. Pellets with cement without plasticizer are below the standard criteria, thus indicating that the plasticizer plays a crucial role in improving this property.

3.3 Abrasion resistance

The resistance of pellets to abrasion is tested by sieving a group of pellets weighing 100 g on a mechanical laboratory sieving device with a sieve of appropriate mesh size (depending on the granule size class being tested) for 5 minutes. The mass percentage of the class being tested is then determined, which should not exceed 5% of the total sample mass.

Table 9 presents the average values of the obtained abrasion resistance results for FA pellets by grain-size classes.

Table 9 Abrasion resistance of pellets by grain-size classes

	1.0-2.0 mm	2.0-3.35 mm	3.35-7.0 mm
FA+C+P	0.52	3.13	3.17
FA+C	1.59	4.86	4.98

The abrasion resistance results demonstrate that these pellets have a high resistance to wear and tear. This is crucial for maintaining the integrity of the pellets over time, which is important in dynamic water treatment systems. Both series exhibited satisfactory abrasion resistance values; however, pellets without a plasticizer showed lower abrasion resistance, reinforcing the importance of the plasticizer in enhancing this property.

3.4 Time of disintegration in water

The time of disintegration of pellets in water is tested by immersing three pellets from each group in water at room temperature and measuring the time needed for complete disintegration. Disintegration is visually determined.

Table 10 presents the average values of the obtained results for time of disintegration in water of FA pellets by grain-size classes.

Table 10 Time of disintegration of pellets by grain-size classes

	1.0-2.0 mm	2.0-3.35 mm	3.35-7.0 mm
		h	
FA+C+P	> 48	> 48	> 48
FA+C	> 48	> 48	> 48

The time of disintegration in water results show consistent values across different pellet series. This suggests that the pellets, regardless of the presence of a plasticizer, maintain their structural integrity for a similar duration when submerged in water. This consistency indicates that all tested formulations are suitable for use in water purification systems where maintaining pellet integrity during the operational cycle is crucial.

4 CONCLUSION

The research demonstrated that FA can be effectively pelletized using cement as a binding agent, with the addition of a plasticizer to enhance mechanical properties. The resulting pellets exhibited satisfactory compressive strength, impact strength, abrasion resistance, and resistance to disintegration in water, making them suitable for use in dynamic water purification systems. By converting FA into pellets, this study offers a practical and cost-effective approach to utilizing this industrial byproduct in wastewater treatment, thereby contributing to both environmental protection and resource recovery. Future research should focus on optimizing the formulation of FA pellets to further enhance their mechanical properties. Exploring different proportions of binding agents and plasticizers can provide deeper insights into developing even more durable and efficient pellets. Additionally, long-term studies on the performance of these pellets in real-world water treatment systems will be beneficial in validating their practical applicability and durability.

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REFERENCES

ALBERT, K.B. and LANGFORD, D. (1998) Pelletizing Limestone Fines- A Study of the Benefits of Pelletized Limestone Fines in the Commercial and Agricultural Market, Mars Mineral, Pennsylvania. pp. 12-29.

ALTERARY, S. and MAREI, N. (2021) Fly ash properties, characterization, and applications: A review. Journal of King Saud University- Science, 33, e101536.

BARTOŇOVÁ, L. (2015) Unburned carbon from coal combustion ash: An overview. Fuel Processing Technology, 134, pp. 136–158.

BAYAT, B. (2002) Comparative study of adsorption properties of turkish fly ashes: I. The case of nickel (II), copper (II) and zinc (II). Journal of Hazardous Materials, 95, pp. 251–273.

IYER, R.S. and SCOTT, J.A. (2001) Power station fly ash- A review of value-added utilization outside of the construction industry. Resources, Conservation and Recycling, 31, pp. 217–228.

LANZERSTORFER, C. (2018) Fly ash from coal combustion: Dependence of the concentration of various elements on the particle size. Fuel, 228, pp. 263–271.

MOHAN, S. and GANDHIMATHI, R. (2009) Removal of heavy metal ions from municipal solid waste leachate using coal fly ash as an adsorbent. Journal of Hazardous Materials, 169, pp. 351–359.

PARK, J.H., EDRAKI, M., MULLIGAN, D. H., and JANG, S. (2014) The application of coal combustion by-products in mine site rehabilitation. Journal of Cleaner Production, 84, pp. 761–772.

YAO, Z., JI, X., SARKER, P., TANG, J., GE, L., XIA, M., and XI, Y. (2015) A comprehensive review on the applications of coal fly ash. Earth-Science Reviews, 141, pp. 105–121.

ZHUANG, X.Y., CHEN, L., KOMARNENI, S., ZHOU, C.H., TONG, D.S., YANG, H.M., YU, W.H., and WANG, H. (2016) Fly ash-based geopolymer: Clean production, properties and applications. Journal of Cleaner Production, 125, pp. 253–267.

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Original scientific paper

WELL COMPLETION OF SUSPENDED AND ABANDONED WELLS FOR THE PRODUCTION OF THERMAL AND ELECTRICAL ENERGY

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Abstract: Suspended and abandoned wells present a considerable opportunity for renewable energy production, whether in the form of thermal, electrical, or combined energy. By utilizing existing infrastructure to harness these forms of energy, it is possible to reduce negative environmental impacts while simultaneously increasing energy efficiency and sustainability. This approach contributes to reducing dependence on fossil fuels and promotes the development of technologies based on renewable energy sources. Suspended wells offer the advantage of being immediately ready for use when needed, making them an efficient solution. In this paper, completion of suspended and abandoned wells for the production of thermal and/or electrical energy is presented.

Keywords: well completion, suspended well, abandoned well, thermal energy, electrical energy

1 INTRODUCTION

Wells whose production is no longer economically viable are either suspended or abandoned. (Templeton et al., 2014). Due to their depth, which ranges from 1000 m to over 2000 m, such wells reach the warmer layers of the Earth's crust (Milivojević, 2011) and represent a significant untapped geothermal potential (Ilić et al., 2023, Jandroković,2021). Suspended and abandoned wells present a considerable opportunity for renewable energy production, whether in the form of thermal, electrical, or combined energy. By utilizing existing infrastructure to harness these forms of energy, it is possible to reduce negative environmental impacts while simultaneously increasing energy efficiency and sustainability. This approach contributes to reducing dependence on fossil fuels and promotes the development of technologies based on renewable energy sources. Depending on the temperature at the bottom of the well, suspended and abandoned wells

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can be used to produce thermal and/or electrical energy (Templeton et al., 2014; Ilić et al., 2023). In this paper, completion of suspended and abandoned wells for the production of thermal and/or electrical energy is presented.

2 SUSPENDED WELLS

Well suspension is the process of temporarily shutting down a well, allowing it to be reactivated and used again in the future. Wells that have been suspended are temporarily out of use, but there may be a future need for their reactivation, for purposes such as the development of oil, gas, and condensate fields, the exploitation of geothermal, industrial, and mineral waters, underground oil and gas storage, or the disposal of industrial waste. Well suspension can be divided into two main types: long-term and short-term suspension.

Long-term suspension includes all procedures and measures applied when it is expected that the well will be out of service for more than a year. This type of suspension requires thorough preparations to ensure that the well remains in a stable condition during an extended period of inactivity, with minimal risk of damage. On the other hand, short-term suspension refers to situations when the well is out of use for up to one year. This approach involves less extensive protective measures but still ensures the functionality of the suspended well during the shorter timeframe (API recommended practice, 2009; Instruction on the procedure for the abandonment, conservation of wells, and the equipment of their wellheads and casings, 2010).

Well suspension is a complex process that consists of several key phases to ensure the long-term integrity of the well. Below are the basic phases of this process:

1. Preparatory work – Before starting suspension, a detailed inspection of the well is required. This inspection includes assessing the technical condition of the casing, checking the equipment at the wellhead, and analyzing the surrounding environment. Afterward, project documentation is created, which describes the suspension procedure in detail, considering the specific geological and ecological characteristics of the location. Additionally, all materials and equipment, such as cement, drilling fluids, and suspension chemicals, need to be secured to ensure the smooth execution of the process.

2. Well suspension process – The first phase in well suspension is the isolation of the production layers, achieved by placing cement plugs. The height and exact placement of these plugs are determined based on the geological conditions of the well. Afterward, the well is filled with a neutral, anti-corrosive fluid to protect it from corrosion and contamination. The wellhead must be securely sealed to prevent unauthorized access and the entry of surface water or other contaminants. Additional protective equipment, such as pressure control devices, can be installed at the wellhead to ensure long-term suspension.

3. Monitoring and maintenance during suspension – During the suspension period, the well must be continuously monitored. This includes regular inspections of the wellhead, the integrity of the casing, and the level of suspension fluid. All necessary maintenance work, including replenishment of suspension fluid and equipment repairs, must be performed in a timely manner. All activities and inspections are recorded in the well's technical documentation, allowing for the tracking of its condition throughout the suspension period.

4. De-suspension procedure – When the well needs to be reactivated, the de-suspension process is carried out according to a pre-established plan in the project documentation. This process involves removing the drilling fluid and drilling out the cement plugs. The wellhead equipment is either repaired or reinstalled, and the well undergoes necessary pressure testing before being put back into operation. A final inspection is conducted to ensure that the well is in good condition and ready for safe and efficient exploitation (Instruction on the procedure for the abandonment, conservation of wells, and the equipment of their wellheads and casings, 2010; API Recommended Practice, 2009).

3 ABANDONED WELLS

Well abandonment is the process of permanently closing a well that is no longer in use. This process involves placing cement plug inside the well to ensure stability and prevent further fluid intrusion. Following this, the free section of the production casing is cut to remove unnecessary parts. Another cement plug is then placed to further secure the well, located just below the wellhead. Once this is done, the blowout preventer is dismantled, removing all remaining equipment from the well, and a cover cap is installed at the wellhead. Finally, the land where the well was located is restored to its original state and repurposed for agricultural or other uses, which includes the restoration of vegetation and the adaptation of the land for future use (Soleša et al., 2002; Instruction on the procedure for the abandonment, conservation of wells, and the equipment of their wellheads and casings, 2010).

Wells that need to be abandoned can be divided into four main categories, depending on the reason for their closure:

1. Wells that have fulfilled their purpose: These wells have completed their planned tasks, whether related to exploration, production, or other technological activities. This includes wells that have reached the end of their productive life, wells used for experiments, and those that served as underground storage facilities.

2. Wells abandoned for geological reasons: This category includes wells that encountered unfavorable geological conditions, such as non-reservoir zones, or wells that could not reach the projected depth due to obstacles like collapses or other geological anomalies.

3. Wells abandoned for technical reasons: These wells are abandoned due to technical problems, such as equipment failures, corrosion, or natural disasters. Wells that suffered significant damage during operation or were affected by poor site conditions also fall into this category.

4. Wells abandoned for technological, ecological, or other reasons: This category includes wells abandoned due to non-compliance with environmental standards, inadequate equipment, or prolonged inactivity. It also includes wells located in restricted areas or unsuitable for further exploitation due to changed circumstances (Instruction on the procedure for the abandonment, conservation of wells, and the equipment of their wellheads and casings, 2010; API recommended practice, 2009).

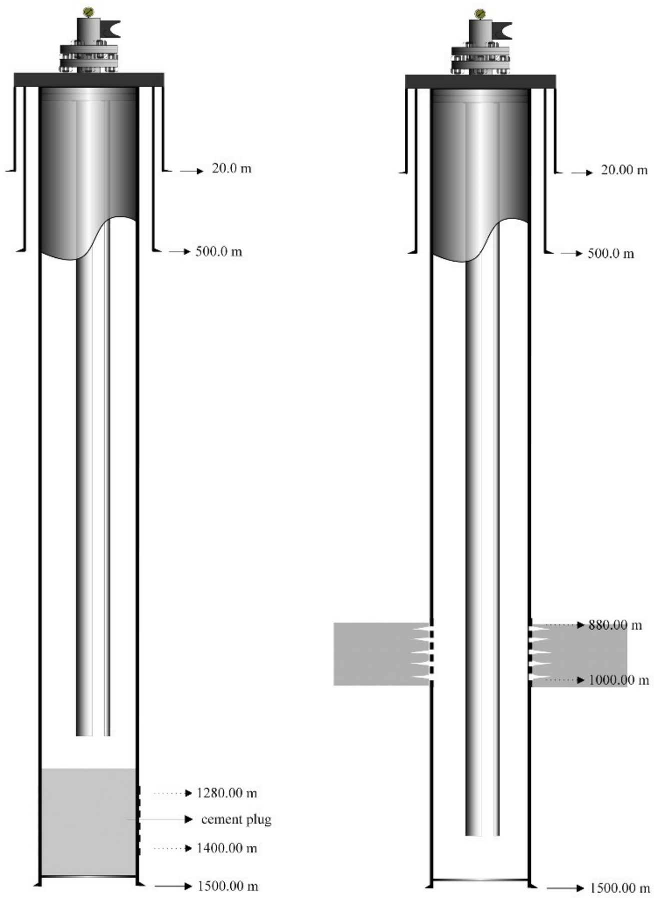
4 WELL PREPARATION FOR THE PRODUCTION OF THERMAL AND ELECTRICAL ENERGY

4.1 Suspended wells

Suspended wells offer the advantage of being immediately ready for use when needed, making them an efficient solution for temporarily inactive wells (Templeton et al., 2014)

To use a well for thermal and electrical energy production, it is necessary to isolate the entire production interval to prevent the mixing of the working fluid with formation fluids (oil, gas, or formation water). This is achieved by cementing all perforations and/or installing a cement plug. If the perforations are located at the bottom of the well, a cement plug is installed. However, when the perforations are not located at the bottom of the well, and to maximize the thermal energy from the well's lower sections, the perforations are cemented (Forward-Looking Framework for Accelerating Households' Green Energy Transition, 2024–2026; Templeton et al., 2014, Ganić,2024).

Figure 1 shows a schematic representation of a well with (a) a cement plug and (b) cemented perforations. Tubing is installed in the well, which is used for circulating the working fluid. The heated fluid moves from the bottom of the well to the surface, and after being used and cooled, it is returned to the same well through the annular space for reheating. This continuous circulation ensures that the heated working fluid is consistently brought to the surface.



a) b)

Figure 1 Schematic representation of a well with a) a cement plug and b) cemented perforations

4.2 Abandoned wells

On the other hand, abandoned wells (Figure 2) require higher costs for reuse, as the process involves additional tasks such as the removal of cement plugs, reopening the well, and reinstalling equipment. These additional steps make the use of abandoned wells more complex and expensive compared to suspended wells (Templeton et al., 2014). Figure 3 shows an abandoned well with a cover cap.

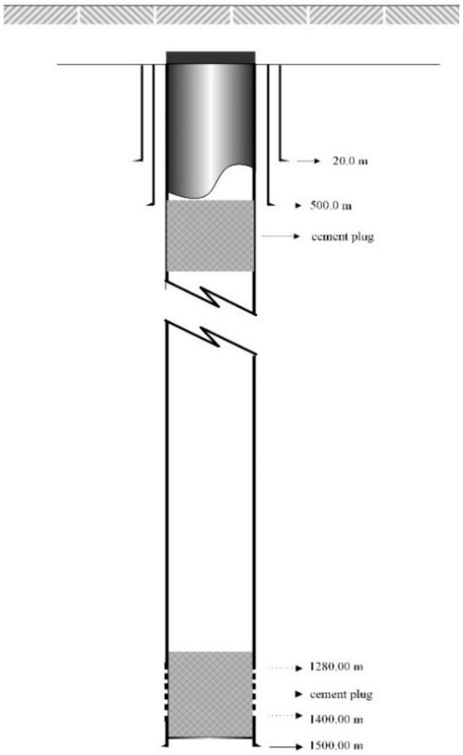


Figure 2 An abandoned well

Figure 3 An abandoned well with a cover cap

The most important procedure is the reinstallation of the production casing, which was cut during the abandonment process. This is achieved by welding a new section of the production casing. Figure 4 shows a detailed view of the welded production casing.

Figure 4 A detailed view of the welded production casing

Figure 5 schematically shows an abandoned well equipped for the production of thermal and electrical energy.

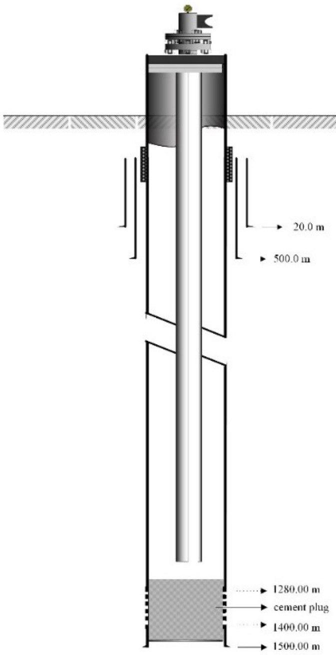


Figure 5 Schematic representation of an abandoned well equipped for the production of thermal and electrical energy

The surface equipment includes a blowout preventer, which is the same for both suspended and abandoned wells that have been re-equipped for production, as shown in Figure 6.

Figure 6 A blowout preventer

5 CONCLUSION

The reuse of suspended and abandoned wells for the production of thermal and electrical energy represents an efficient and sustainable solution. The use of these wells directly enables the valorization of an unused energy resource.

Suspended wells can be more easily repurposed at lower costs, while abandoned wells require additional work but still offer significant energy potential. This approach reduces dependence on fossil fuels and utilizes existing infrastructure, contributing to environmental sustainability.

Completion of suspended and abandoned wells for the production of thermal and/or electrical energy involves significantly lower costs compared to drilling new deep wells, which can reach up to 2 million dollars. Therefore, suspended and abandoned wells are not only an energy resource but also a significant economic asset. By utilizing this existing infrastructure, initial investments are reduced, increasing the economic viability of transitioning to renewable energy sources.

Suspended and abandoned wells are used for circulating the working fluid through the tubing to the surface, after which the utilized cooled fluid is returned to the same well through the annular space for reheating. Through this circulation, heated working fluid from the well is continuously brought to the surface.

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REFERENCES

API recommended practice, 2009. Environmental Protection for Onshore Oil and Gas Production Operations and Leases

GRANIĆ, T. (2024) Geothermal wells cementing. (MSc), University of Zagreb Faculty of Mining, Geology and Petroleum Engineering

ILIĆ, M., ŽIVKOVIĆ, M., DANILOVIĆ, D., CRNOGORAC, M., KAROVIĆ MARIČIĆ, V., TOMIĆ, L. (2023), Determination of the theoretical thermal potential of abandoned oil and gas wells, Tehnika, 6, pp. 667-672

JANDROKOVIĆ, M. (2021), Completion of geothermal wells. (MSc), University of Zagreb Faculty of Mining, Geology and Petroleum Engineering

MILIVOJEVIĆ, M. (2011) Geothermology and geothermal energy. Belgrade: Faculty of Mining and Geology

SOLEŠA, M., MALOGAJSKI, S. (2022) Workover and stimulation operations in oil and gas wells. Novi Sad: DIT NIS-Naftagas

TEMPLETON, J.D., GHOREISHI-MADISEH, S.A., HASSANI, F., AL-KHAWAJA, M.J. (2014) Abandoned petroleum wells as sustainable sources of geothermal energy, Energy, 70, pp. 366-373

Instruction on the procedure for the abandonment, conservation of wells, and the equipment of their wellheads and casings (RD 08-492-02), 2010. Series 08. Issue 8.

Forward-Looking Framework for Accelerating Households' Green Energy Transition, Science Fund of the Republic of Serbia, 2024-2026

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Review paper

CRITERIA FOR DECISION-MAKING FOR THE BEST RECLAMATION SOLUTION

Radmila Gaćina[1], Sanja Bajić[1], Bojan Dimitrijević[1], Branko Gluščević[1]

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Abstract:

Mine site reclamation is a relevant step in maintaining ecological balance after mining activities. Although mining activities provide many economic benefits, they often have a negative impact on the environment. These environmental problems require effective and sustainable solutions. To minimize the effects of mining, environmental management is obligated to stabilize the land, so it is productive after mine closure and leads to the best possible purpose. Regulatory authority sets out the criteria for reclamation to be accomplished by the mine reclamation program such as compliance, land re-contouring, revegetation, and final completion.

Keywords: mine reclamation, post-mining land-use, mine land suitability analysis (MLSA), criteria

1 INTRODUCTION

The exploitation of mineral resources has been one of the prime industries of Serbian economic develop. The environmental surroundings are complex in Serbian mines, so it is needed to carry out land recultivation after mining to reclaim ecology. Recultivation and reclamation of the landscape after mining exploitation has a complex multidisciplinary character and requires a series of activities: technical-technological, engineering-geological, hydrotechnical, spatial planning, agronomic and forestry, business, social, etc. The aim of the mentioned activities is to restore natural functions to degraded land and create conditions for new functions of the area (agriculture, forestry, tourism and recreation, park complexes, industry).

According to Liu, the mining surface provides crude materials and energy for economic construction and for people's working, but the development of mineral resources inevitably causes damage to land resources. The reuse of deserted mining areas directly restricts the sustainable development of the mining area (Liu, 2017). In his work, Guobin

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assumes that the direction of recultivation should be determined, which in turn requires land evaluation. (Guobin, 2020). Based on ordering and optimizing multiple plans, Land reclamation benefits in mining areas can be examined (comprehensive evaluation, ranking, and optimizing the plans based on some evaluation criteria (Yu, 2020).

The reclamation process as a business system, modeled through its sub-processes: technical recultivation, biological recultivation, monitoring of the living and working environment, and management is relayed through the management process, which consists of the sub-processes of planning, organizing, monitoring the implementation and control of the implementation of business activities (Dimitrijević, 2014). The principal model of reclamation management is shown in Figure 1.

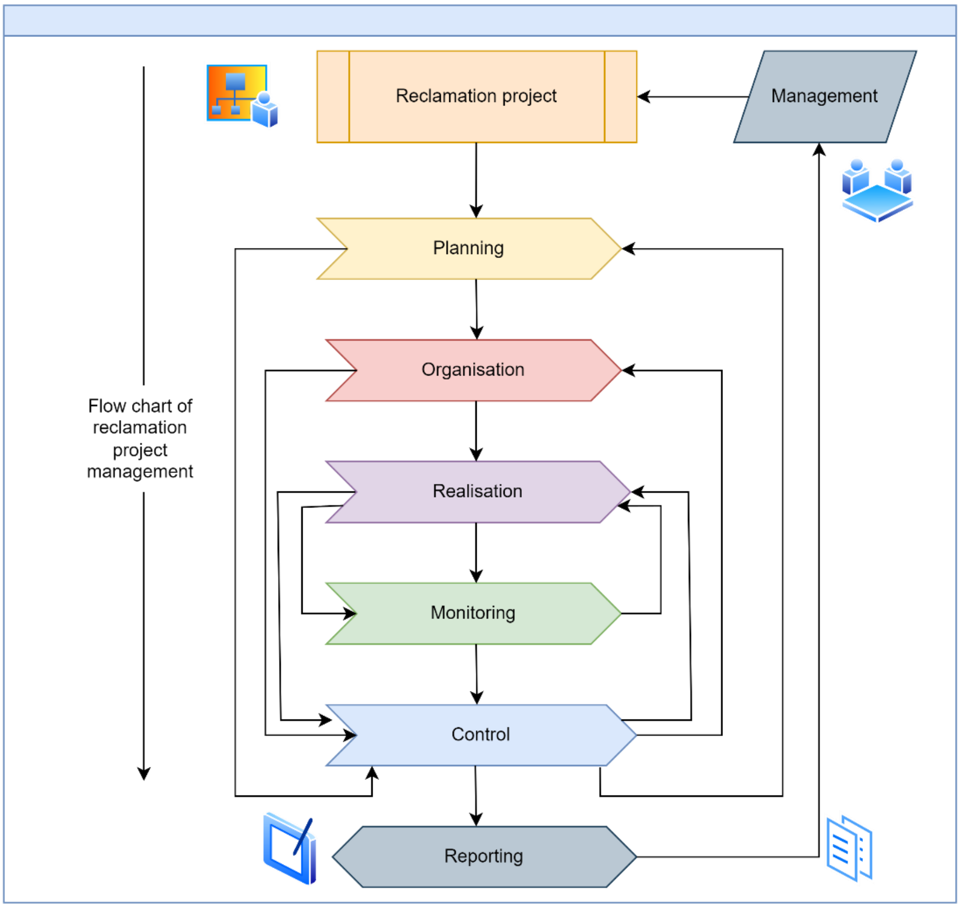

Figure 1 The principal model of recultivation management

Land reclamation includes the following - physical soil stabilization, monitoring surface and groundwater quality, topsoil solution, erosion, landscaping, the re-vegetation, and wildlife habitats. For each of these stages of recultivation, it is important to determine the criteria based on which individual optimization of land use can be carried out.

Reclamation is constantly taken out throughout the production phases at the mining area and is intensified during the mine closure. At the beginning of working, the vegetation is cleared up and the topsoil is removed (stored in a process called "topsoil management"). The next stage starts after the mining area has been excavated and already announced as finished and reclaimed. In this last stage, the land area is prepared for revegetation and includes observance work. Figure 2. shows the range of reclamation stages and affiliated activities.

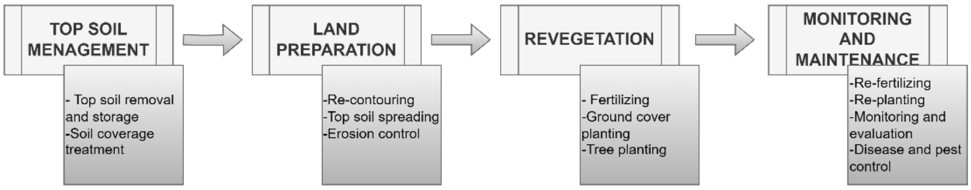

Figure 2 Mining reclamation stages

For mine planning and design, identifying proper Post-Mining Land Use is crucial for achieving good environmental quality regeneration.

2 LITERATURE REVIEW

Mine exploitation usually has devastating effects on the environment, due to large land use and occupation of big areas. Recultivation plans should be submitted at the same time as the mine exploitation plans. Mine land reclamation includes rehabilitation measures to impair the adverse environmental impacts of mine works throughout the mining process (Setiawan et al., 2021). Sengupta in his paperwork defines the aim of reclamation, as establishing a stable landscape that is aesthetically and environmentally suitable with the ambient undisturbed area (Sengupta 1993).

The first impression in much of the landscape devastated by mining is one of dereliction and negligence, but a mined land can be sustained as an Industrial or Commercial area if it is convenient and have a broad range of potential role such as, Recreational Areas, Swimming Pools, Theme parks or an open-air museum In their paperwork Masoumi and others defined Land suitability analysis as a basic step in sustainable reclamation planning and design. They also propose different types of reclamation alternatives that could be received for post-mining land use, such as agricultural land, industrial areas, residential land, recreation areas, etc. (Masoumi at al., 2014).

The resolution for the most appropriate land use for every part of the mined area is based on the findings got from the characteristics of locality, the opinions of experts in that field, the development plans of local authorities and population, the legal environmental regulations, and the environmental constraints (Palogos at al., 2017). Land reclamation experts elect the decision parameters and their optimal benefit for each land purpose. In Table 1 have been shown eight-group, common land-use practices after recultivation of degraded land common in literature have been shown, consisting of 24 individual land-purposes.

Table 1 Common post-mining land use practices

Alternatives number	*Land use type*	*Realized Post-mining Land Uses*
A1	***Agronomy***	Arabble farmland, Gardening, Grassland or hay-land,
A2	***Forestry***	Woodland, Wood production, Shrubs and natural forestation
A3	***Lake / pool***	Sailing, Swimming, Aquaculture, or supply of water
A4	***Intense Recreation***	*Sport fields, Hunting, Swimming, Fishing*
A5	***Non-Intense Recreation***	*Open green space - parks, Open space Museum or exhibition of mining innovation*
A6	***Structural***	*Housing, Industrial, Educative, A sustainable society*
A7	***Preserving***	*Wild habitat, Supply of water*
A8	***Filling the Pit***	*Use as landfill (last purpose)*

Some of these land uses have been very successful, while others have met off fail. Several studies show that without land use suitability analysis sometimes the results are unacceptable. Therefore, it is necessary to observe the standard criteria for choice of land purpose use.

3 HIERARCHICAL FRAMEWORK FOR MINE LAND SUITABILITY ANALYSIS

In their paperwork, Mborah and others set the ultimate objective of post-mine land-use and reclamation planning. They are identifying convenient alternate land uses which mined land could be put. This can provide that land-use of specific location will be capable of supporting either the earlier land-use or pre-mining environment (Mborah et al., 2016).

According to Wang and others, there are several deficiencies in the present assessment of land reclamation quality in mining zone. Also, there is the absence of an established set of evaluation index systems and standard criteria, as well as the use of traditionally sampling techniques, which are long term, expensive and in effectiveness (Wang et al., 2023).

The major challenge for deciding of land purpose after reclamation is selection of variables that must be considered. Criteria identified as insignificant in the land use election process involve land type characteristics (physical, biological ones and also cultural characteristics), location, types of mining actions, legal act requirements, needments of the local community, ownership, economic, environmental, technical and social factors.

Assessment attributes from literature are divided into four groups as criteria for the formation of a hierarchical level of mined land suitability. The overall goal and criterial level (Technical, Economical, Mine site Factor, Social) have been shown in Figure 3.

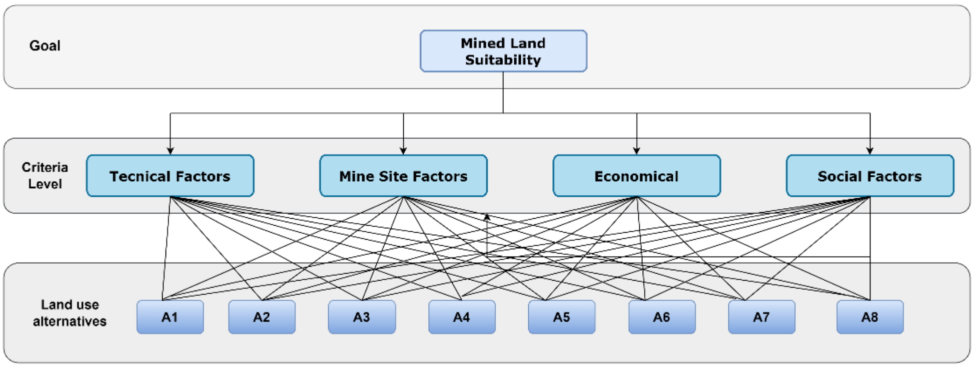

Figure 3 Hierarchical structure of Mined Land Suitability Analysis

Then, each main criterion is extended to the next attribute level.

4 CRITERIA

Technical Criteria denote limits that each one has affinity to compel decision-makers to a separate post-mining land-use that is the most convenient for technological shortcomings associated to that attribute. As shown in Figure 4, The Technical Factors include attributes such as size and shape of mined land area, reclamation techniques availability, distance to nearest supply of water, availability on the market, current land-use in surroundings, mine area prosperity, structural geology, remoteness from special services, environmental pollution, potential of extreme events, re-using potential of mine facilities, quality of landscape.

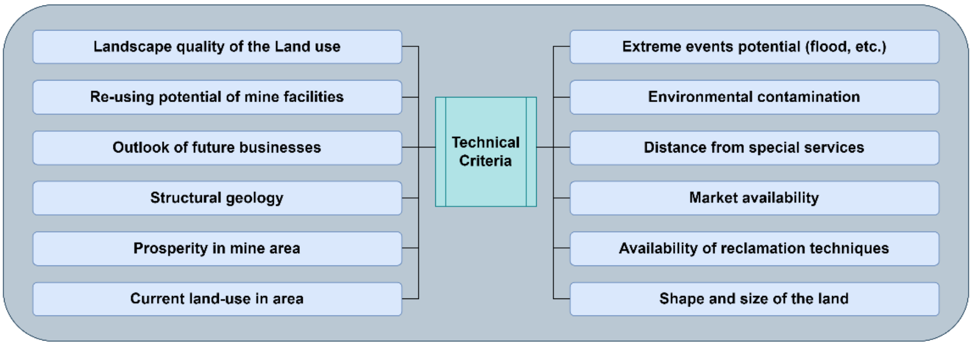

Figure 4 Technical Criteria for MLSA

The Mine terrain - site Criteria presents specific attributes that have impact on decision and consist of three attribute groups - Soil, Climate and Topography as shown in Figure 5. In general, Mine Site Factors are devided; Soil (soil's physical properties and chemical properties), Topography (slope, elevation, surface relief, Exposure to sunshine) Climate (temperature, evaporation, frost freedays, precipitation, wind speed, air moisture, hydrology of surface and groundwaters).

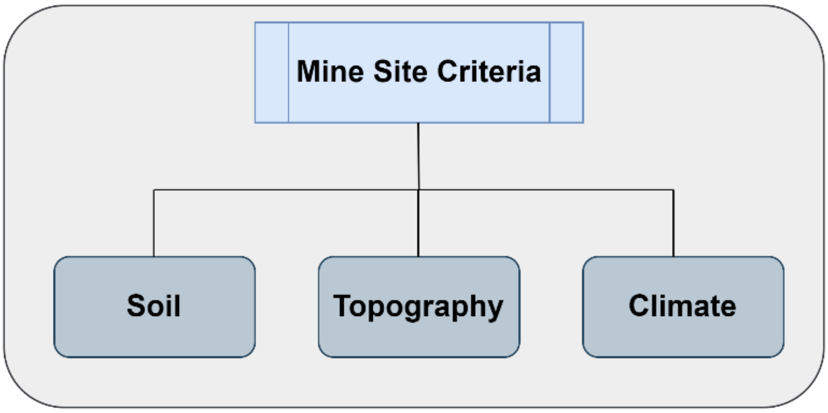

Figure 5 Mine terrain Criteria for MLSA

Economic Criteria are shown in Figure 6, they include attributes: in first place, Costs (Operational, Capital and Maintenance and Monitoring), Changes in real estate values, increase in governmental incomes, positive changes in real estate values and increase in local community.

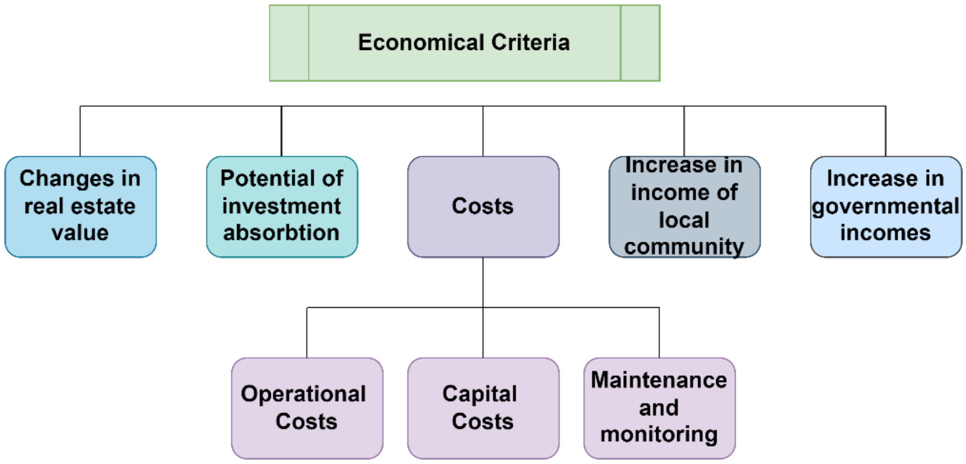

Figure 6 Economic Criteria for MLSA

Finally, Social Criteria are of main significance and they are shown in Figure 7, including attributes: positive changes in livelihood quality, ecological acceptability, need to specialist workforces, opportunities for employment, availability the public education, frequency of passing through mine site, tourism attraction, stakeholders engagement, impact on immigration to the local area, the proximity of the mine location to populated centers, mining company and government policy, consistency with local requirements.

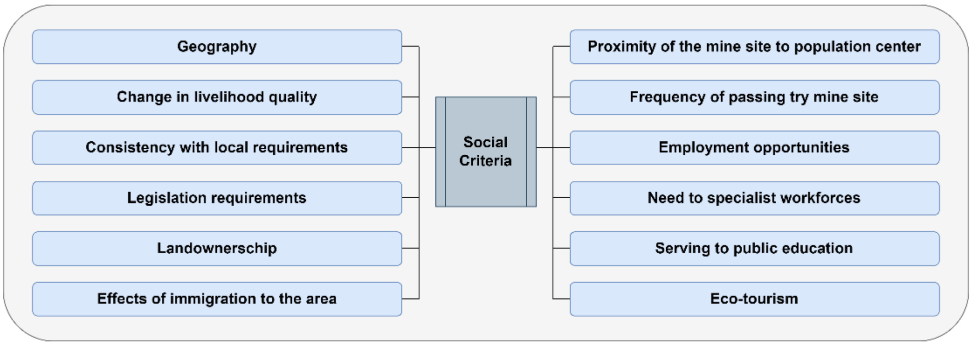

Figure 7 Social Criteria for MLSA

During the process of mine land suitability analysis, society, community and stakeholders should be consulted, when a post-mining land-use is dissimilar to the pre-mining land-use. The existing landowners and neighbors should be consulted even if they are small mines. It is very significant that the post-mining land-use would be receptive to the local society.

5 CONCLUSION

Reclamation of land degraded by mining should be the most important responsibility of companies. Mine exploitation is time bounding and must be well planned before mining begins, so requiring that post-mining activities meet the needs of local society and the environment. Mine site reclamation aims to upgrade the mined land environment, making it more productive by utilizing it in proper way. In this paper, in the evaluation, to the greatest extent possible, factors that influence the suitability of land reclamation and the direction of land reclamation are included.

Research into this paperwork has shown that much information on the subject of criteria for selection land use are accessible in the literature. Also, it shows that many successes were accomplished all over the world. The principal goal of some specific reclaimed post-mining land use must be achieving success in economic and sustainable outcomes respecting human needs and protecting environment in surroundings. Community involvement in selection land use after reclamation and use process stays one of the basic factors to a prosperous reclamation.

Reclamation Criteria can be used to restore other disturbed lands with similar contexts, and not only provide theoretical guidance for ecological restoration of post-mining areas. In conclusion, mine reclamation has as a goal to restore mined-out areas to a state of acceptable social and ecological.

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REFERENCES

DIMITRIJEVIĆ, B. (2014) Optimization of the management of surface coal mine reclamation processes. doctoral dissertation, University of Belgrade.

LIU, X.Y.; BAI, Z.K.; ZHOU, W.; CAO, Y.J.; ZHANG, G.J. (2017) Changes in soil properties in the soil profile after mining and reclamation in an opencast coal mine on the Loess Plateau, China. Ecol. Eng. 2017, 98, 228–239

MASOUMI, I.; NARAGHI, S.; RASHIDI-NEJAD, F.; MASOUMI, S. (2014) Application of fuzzy multi-attribute decision-making to select and to rank the post-mining land-use. Environmental earth sciences, 72, 221-231.

MBORAH, C.; BANSAH, K. J.; BOATENG, M. K. (2016) Evaluating alternate post-mining land-uses: A review. Environment and Pollution, 5(1), 14-22.

PALOGOS, I.; GALETAKIS, M.; ROUMPOS, C.; PAVLOUDAKIS, F. (2017) Selection of optimal land uses for the reclamation of surface mines by using evolutionary algorithms. International Journal of Mining Science and Technology, 27(3), 491-498.

SENGUPTA, M. (1993) Environmental Impacts of Mining: Monitoring, Restoration, and Control; CRC Press LLC: Boca Raton, FL, USA.

SETIAWAN, I. E., ZHANG, Z., CORDER, G.; MATSUBAE, K. (2021). Evaluation of environmental and economic benefits of land reclamation in the Indonesian coal mining industry. Resources, 10(6), 60.

TANBG, G.; ZHANG, Z.; LV, Q.; HAO, R.; WANG, K. (2020). Suitability evaluation for land reclamation of nonmetallic mines in Xinjiang, China. Mathematical Problems in Engineering, 2020, 1-12., https://doi.org/10.1155/2020/4250814

WANG, J.; ZHAO, F.; YANG, J.; LI, X. (2017) Mining Site Reclamation Planning Based on Land Suitability Analysis and Ecosystem Services Evaluation: A Case Study in Liaoning Province, China. Sustainability 2017, 9, 890. https://doi.org/10.3390/su9060890

WANG, S.; GUO J.; YU, Y. et al. (2023) Quality evaluation of land reclamation in mining area based on remote sensing. Int J Coal Sci Technol 10, 43 (2023). https://doi.org/10.1007/s40789-023-00601-9

YU, X.; MU, C.; ZHANG, D. (2020) Assessment of Land Reclamation Benefits in Mining Areas Using Fuzzy Comprehensive Evaluation. Sustainability 2020, 12, 2015. https://doi.org/10.3390/su12052015

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Original scientific paper

OPTIMAL ARTIFICIAL LIFT METHODS FOR SMALL OIL FIELD PRODUCTION

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Abstract: Artificial lift methods are essential for maintaining productivity of oil wells that are depleted or lack sufficient natural energy for self-sustaining production. Properly selected artificial lift methods enable fluid production continuity, ensure stability and maintain long-term economic viability, especially when the reservoir can no longer support natural fluid lift to the surface. On the small oil field X, the initial production phase utilized natural flow methods, whereas declining reservoir energy prompted the implementation of sucker rod pumps (SRP), which were later replaced by electrical submersible pumps (ESP). Performance analysis revealed that ESP systems encountered challenges, including motor overheating due to reduced fluid inflow and insufficient cooling. In contrast, SRP systems exhibited more stable and reliable performance under the specific operating conditions of oil well at field X. This study investigates artificial lift methods, and through analyzing SRP and ESP system performance, concludes that SRP systems are more suitable for sustained and efficient production on small oil field X.

Keywords: artificial lift methods, electrical submersible pump, sucker rod pump, small oil fields, system performance analysis

1 INTRODUCTION

With increasing global energy demand and limited new hydrocarbon reserves, maintaining current production levels is essential to meet market needs. Artificial lift methods play a crucial role in achieving this goal (Flatern, 2015). These processes enable reservoirs to produce oil at the desired rate (Ugochukwu Ilozurike Duru, 2021). Although there are various artificial lift methods, they can generally be divided into two main categories: pump systems and gas lift (Ladopoulos, 2020). Pump systems include sucker

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rod pumps (SRP), electrical submersible pumps (ESP), progressing cavity pumps (PCP), hydraulic jet pumps (HJP), and plunger lift systems (PP) (Ugochukwu Ilozurike Duru, 2021) (Crnogorac, 2020).

Figure 1. shows the global application of artificial lift methods, where sucker rod pumps account for 82%, gas lift for 10%, and electric submersible pumps account for 4%. Hydraulic and progressing cavity pumps have a combined share of 2% (Crnogorac, 2020).

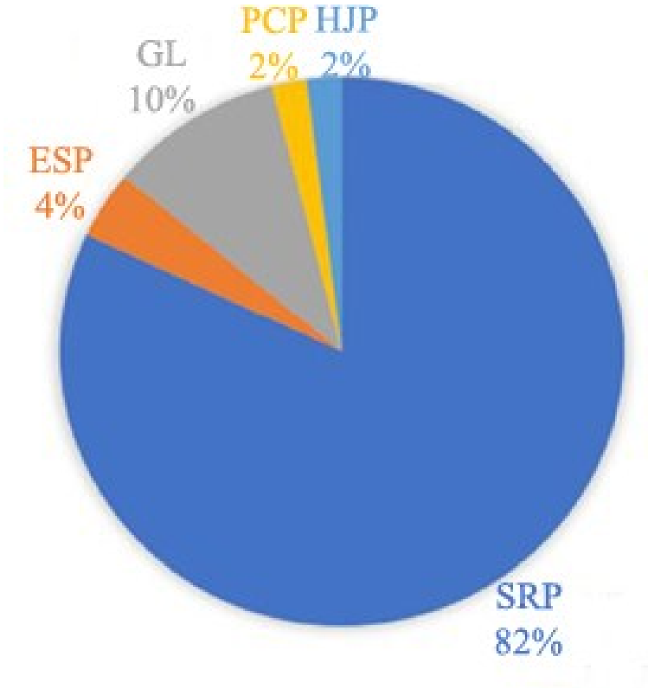

Figure 1 Global Prevalence of Artificial Lift Methods (Crnogorac, 2020)

Figure 2. highlights the most important artificial lift methods. For example, electrical submersible pumps (ESP) and gas-lift systems are often suitable for offshore wells because they can support high production rates and operate at great depths. These systems are efficient under stable operating conditions and provide consistent productivity.

On the other hand, sucker rod pump (SRP) systems are typically the best choice for onshore wells. Although they require more surface space, these pumps are reliable, easy to maintain, and often represent a more economical solution in cases where total installation and maintenance costs are significant factors (Flatern, 2015) (Ugochukwu Ilozurike Duru, 2021) (Akchay L. Pandit, 2015).

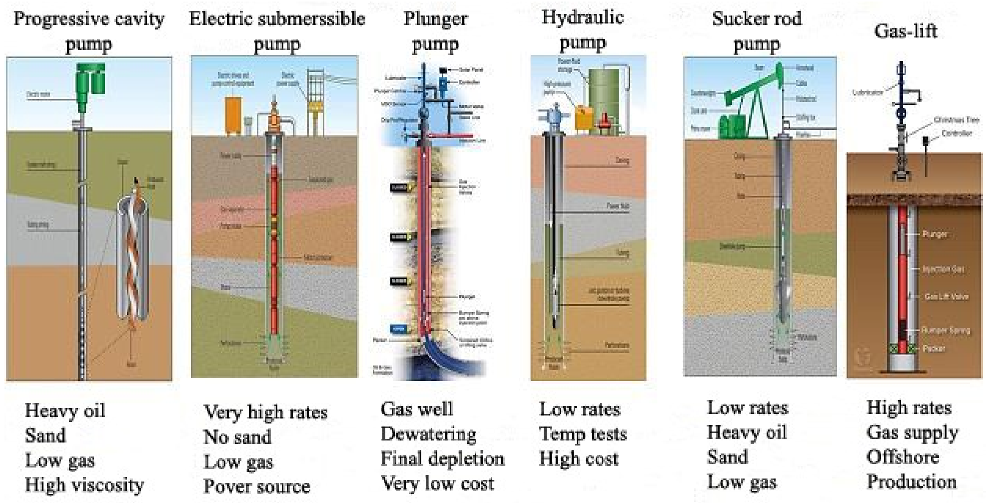

Figure 2 Most Common Artificial Lift Methods and Their Application Conditions and Areas (Ugochukwu Ilozurike Duru, 2021)

A primary characteristic of small oil and gas fields is that exploration investments and development costs are relatively high, with limited space for production management expenses. This makes production highly sensitive to fluctuations in oil prices and production costs. It is well-known that oil prices on the global market are variable, influenced by specific factors tied to the immediate and strategic objectives of economically leading countries, where political factors are dominant. While there are periods of relatively stable prices, there are also times of rapid price changes, adding complexity to managing production on small oil fields.

In managing oil and gas production in small fields, it is not possible to influence capital production costs or the market price of crude oil and natural gas. Consequently, variable costs, i.e., production management costs (operational expenses) are the element through which production profitability must be regulated to ensure economic viability.

2 CHARACTERISTICS OF ELECTRICAL SUBMERSIBLE PUMPS (ESP) AND SUCKER ROD PUMPS (SRP)

Electrical submersible pumps (ESP) and sucker rod pumps (SRP) represent two of the most common artificial lift methods. These two technologies play a key role in oil production but differ significantly in their operating principles, productivity, well condition resilience, and maintenance costs, as detailed below.

2.1 Operating principle of ESPs and SRPs

Electric Submersible Pumping (ESP) systems operate based on the centrifugal principle, utilizing centrifugal force to lift fluids. The ESP uses impellers that rotate at high speeds to generate centrifugal force, lifting fluid from the wellbore to the surface. The pump motor is submerged in the fluid along with the pump, allowing efficient energy conversion and enabling the lift of large fluid volumes. ESP systems are known for their ability to handle high flow rates and are suited for stable well conditions where free gas content is low, and the fluid is relatively clean (Suelem Sa Dela Fonte, 2022).

In contrast to the ESP, the sucker rod pump (SRP) utilizes a mechanical piston and rod system. A surface motor drives the sucker rods, transferring energy deep into the well, where a piston moves up and down, lifting fluid to the surface. SRP systems are better suited for wells with lower flow rates and higher gas content or solid particles in the fluid. This mechanism is more resilient to changing well conditions and can operate effectively in more complex environments (Okodi, 2017).

2.2 Productivity and resistance to downhole conditions

ESP pumps are designed for high-production wells, with fluid lifting capacities exceeding 400 m^3/day, making them ideal for wells with substantial production potential. However, high concentrations of free gas or sand in the fluid can negatively impact ESP efficiency, as gas creates bubbles that reduce pressure, and sand can damage the impellers. Additionally, high-viscosity oil can present operational challenges for ESP systems (Takacs, 2017).

On the other hand, SRP systems have lower productivity but are significantly more resilient to conditions that may impair ESPs. They perform better in environments with higher free gas content, sand, or viscous fluids, and are suitable for wells where significant water production is expected. This resilience makes SRP systems more appropriate for wells with variable or challenging conditions. SRP systems are also well-suited for wells with low to medium flow rates, where ESP systems may not be economically viable (Sherif Fakher, 2021).

2.3 Installation and maintenance costs of ESPs and SRPs

One of the significant differences between ESPs and SRPs lies in installation and maintenance costs. ESPs require a more complex installation and higher initial costs. In the event of a failure, the pump must be pulled to the surface, that greatly increases repair costs and production downtime. Furthermore, ESP systems require special equipment for monitoring and adjustments, adding to their operational complexity.

SRP systems have a simpler design and lower maintenance costs. Most of the SRP equipment is located on the surface, making it more accessible for maintenance and repairs. In case of a malfunction, it is often possible to service the system without the need for high costly operations to pull the pump from the well (Akchay L. Pandit, 2015).

2.4 Reasons for replacing one artificial lift method with another one

In modern oil well management, the selection of the appropriate artificial lift method plays a critical role in optimizing production and maintaining operational efficiency. Switching from one lifting system to another may be necessary to optimize productivity and reduce operating costs. Based on the unique conditions of the well, properties of the produced fluid, the presence of gas and water, and economic factors, the choice of an artificial lift method or replacement of an existing one is made.

One of the most common reasons for a switch is a change in well conditions. For instance, if a oil well begins to produce higher quantities of gas, sand, or water, sucker rod pumps may be a better choice due to their resilience to such conditions. For example, when water production increases, ESP systems may lose efficiency due to increased pressure and hydraulic complications. In these cases, switching to SRP becomes logical, as SRP systems are better equipped to handle high water cuts and impurities (Clegg, Bucaram, & N.W. Hein, 1993).

Conversely, if the well produces larger volumes of fluid with a low gas content, ESPs become preferable due to their ability to handle high fluid volumes. Their higher productivity can significantly boost the overall production of the well.

Economic factors may also drive a change in lift systems. If the maintenance of an ESP system becomes too costly or complex, the operator may choose to switch to an SRP system to reduce costs and simplify operations. (Clegg, Bucaram, & N.W. Hein, 1993)

2.5 Selection of artificial lift methods for small oil fields

In the context of oil wells in Serbia utilizing artificial lift methods, given that fluid production is relatively low, and most fields are in the mature stage of depletion, sucker rod pumps (SRP) are a significantly more suitable solution. Within the Petroleum Industry of Serbia (NIS a.d., Novi Sad), oil wells employing electrical submersible pumps (ESP) often require transitioning to an intermittent operation mode. However, this approach is not optimal, as ESPs are not designed for intermittent use and are consequently more susceptible to failures and reduced efficiency.

Sucker rod pumps are much better adapted to intermittent operation, as their mechanical system tolerates operational interruptions more effectively and adjusts to the specific conditions of low-productive wells. In such scenarios, SRPs not only offer greater reliability but are also more economically viable for sustained production.

From an economic standpoint, SRPs represent another considerable advantage. NIS a.d. Novi sad- company already possesses sucker rod pumps and has trained personnel for their operation and maintenance, indicating that leveraging existing assets constitutes a more financially prudent option. In contrast, ESPs entail rental and additional costs, rendering their application less cost-effective in the long run.

3 CASE STUDY: CHANGE OF ARTIFICIAL LIFT METHOD AT OIL WELL X-001

At oil field X, few exploitation methods have been employed to date. Initially, natural flow production was present. However, with the decline of reservoir energy, sucker rod pumps were used. These have been partially replaced by electrical submersible pumps (ESP). This paper aims to provide an analysis of which artificial lift method should be considered appropriate for this oil field.

Well X-001, located in the northeastern part of oil field X, reservoir X-1, has been in production since January 1, 2016, with a perforation interval between 2070-2085 meters. The well is equipped with a “Borets ESP DP190” model of electrical submersible pump, installed at a depth of 2030 meters. Following the initial adjustment phase, the well entered stable operation, producing between 18 and 19 m^3 daily, with a dynamic fluid level ranging from 1400 to 1600 meters. The pump temperature fluctuated between 130 and 140 °C.

Over time, a gradual decline in the dynamic fluid level and an increase in pump temperature were observed, culminating on February 11 and April 4, 2017, when two automatic shutdowns of the ESP occurred due to high-temperature protection activation. These situations necessitated production interruptions and further analysis.

In Figure 3, the production profile of well X-001 is presented from the start of production until the well was shut in. It involves total fluid production (Qf) as a green line, which remains stable, water cut (Wc) as a blue line indicating consistently high-water content, and oil production (Qn) as a black line, significantly lower than the total fluid but steady. The dynamic fluid level (Hdin), shown in yellow, fluctuates with noticeable drops, while the temperature (Temp), represented by the red line, increases sharply from 170°C to 185°C at one point. Key operational changes or anomalies are highlighted with blue rectangles, emphasizing shifts in fluid level and temperature.

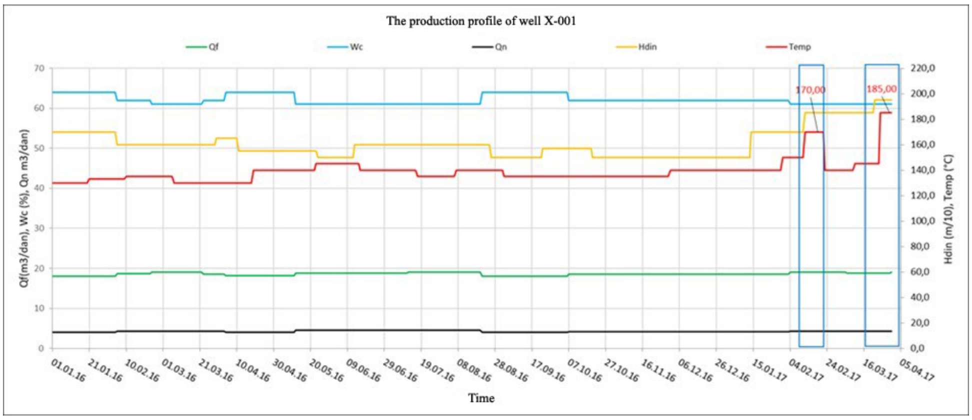

Figure 3 The production profile of well X-001

A detailed analysis of the equipment performance in well X-001 is required, addressing two key questions that will aid in optimizing operations and resolving pump issues. It refers to overheating of the ESP pump and determining the exploitation method for continuous operation.

The performance analysis of the electrical submersible pump (ESP) was done using “Pengtools.com” software, online petroleum engineering software.

Table 1 presents the input data, i.e. characteristics of the electrical submersible pump (ESP), including parameters such as flow rate, fluid properties, and operational conditions essential for the performance analysis.

Table 1 Input data for an ESP

Pump intake depth	2030	m
Tubing outside diameter	73	mm
Tubing inside diameter	62	mm
Coupling outside diameter	86.7	mm
Caseing inside diameter	150	mm
Top of perforation depth MD	2070	m
Liguid flowrate at surface conditions	18	m^3/d
Producing watercut	73	%
Reservoir pressure	80	bar
Reservoir temerature	130	ºC
Specific gravity of oil relative to water	0.85	
Specific gravity of gas relative to air	0.65	
Specific gravity of water	1	
Soluton gas-oil ratio	50	m^3/m^3
Oil density	737.1	kg/m^3
Oil formation volume factor	1.19	m^3/m^3
Oil viscosity	0.63	mPa·s
Z factor	0.94	
Gas densiy	48.3	kg/m^3
Gas formation volume factor	0.016	m^3/m^3
Gas viscosity	0.016	mPa·s
Water densiy	940.8	kg/m^3
Water formation volume factor	1.06	m^3/m^3
Water viscosity	0.22	mPa·s
Productivity index	6.57	m^3/day/bar
Producing gas-oil ratio	100	m^3/m^3
Producing gas-liquid ratio	27	m^3/m^3
Frequency	60	Hz

Table 2 displays the overall results of the calculations performed for the electrical submersible pump (ESP) analysis in Pengtools.

Table 2 The results for the electrical submersible pump (ESP)

Well folowing pressure	P_{wf}	78.2	bar
Pump intake pressure	PIP	74.68	bar
Pump discharge pressure	PDP	143.48	bar
Liguid flowrate at surface conditions	q_{liq}	18	m^3/d
Mixture flowrate at intake	$q_{mixture}$	24.7	m^3/d
Mixture flowrate at intake after separation	$q_{mixture\_sep}$	20.4	m^3/d
Gas into pump before separation	GIP_{before_sep}	23.3	%
Gas into pump after separation	GIP_{after_sep}	7.05	%
Total dynamic head	TDH	742.9	m
Breaking horsepower	BHP	5.14	kW
Breaking horsepower	BHP	6.89	hp

Figure 4 illustrates the characteristic performance curve of the electrical submersible pump (ESP), highlighting its operational efficiency for various flow rates and total dynamic head (TDH) conditions. This curve provides valuable insights into the pump's performance characteristics, including its optimal operating range, efficiency values, and the impact of varying fluid properties on its output.

The horizontal axis represents the flow rate in cubic meters per day, indicating the volume of fluid moved by the pump. The blue line shows the head capacity, reflecting the pump's ability to lift fluid at different flow rates, while the green line represents the pump efficiency, demonstrating how effectively the pump operates across the flow range. The red line indicates the brake horsepower, or the power required by the pump to operate under varying conditions. The yellow shaded area marks the optimal operating range, ensuring reliable and efficient performance, while the blue circle highlights a specific operational point, likely the current or design condition. This diagram helps analyze the pump's suitability for handling oil, water, or fluid mixtures, providing a basis for optimizing production.

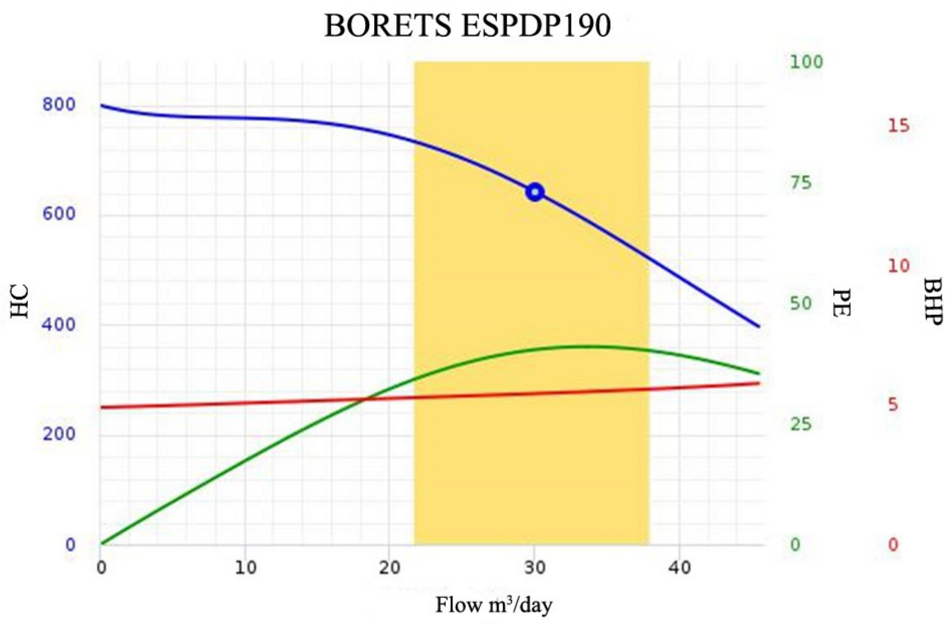

Figure 4 The ESP pump performance curve ("Pengtools.com")

The optimal operating range for this pump is between 20 and 40 m³/day, with the highest efficiency observed around 25 m³/day. Operating within this range will be the most energy-efficient and will provide a good balance between fluid lifting and motor power. However, at the current liquid flow rate of 18 m³/day, the pump's efficiency will be lower than within the optimal range. According to the graph, efficiency falls below 50% at this flow rate. This indicates that the pump will not operate at its energy-optimal level, which could lead to higher operational costs and potential system overloads, ultimately resulting in increased expenses for the same scope of work.

In Figure 5 the relationship between frequency and torque versus flow rate is presented.

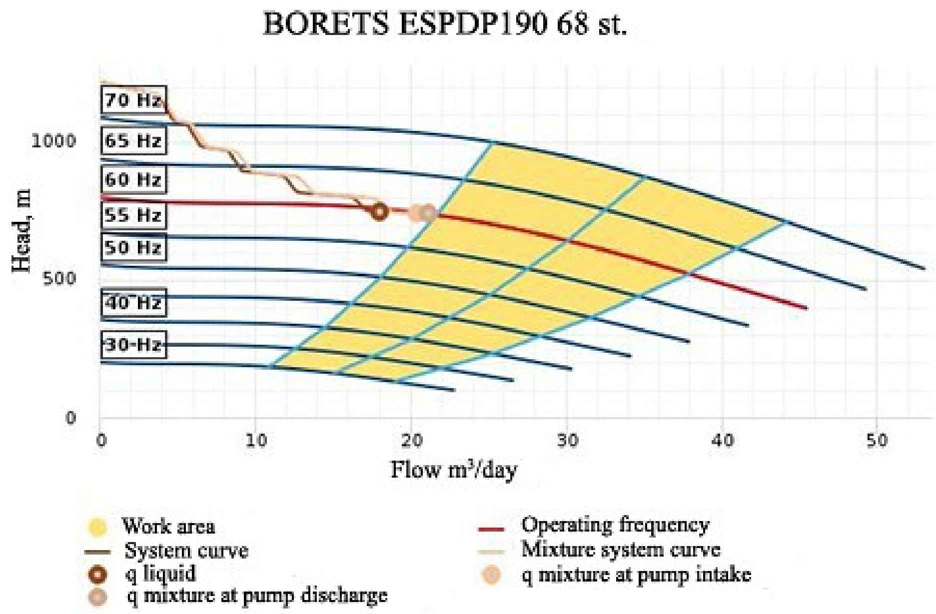

Figure 5 The frequency and torque versus flow rate diagram ("Pengtools.com")

The diagram in Figure 5 shows that the system curve indicates potential stability issues in the pump's operation. This is primarily due to the pump's production of a small volume of fluid, despite its capability to handle significantly large quantities. These instabilities can lead to:

- Inefficient pump operation, which may result in increased energy costs and reduced fluid flow.
- Damage to the pump due to improper functioning, particularly if the fluctuations become excessively large.

4 SELECTION OF A NEW ARTIFICIAL LIFT METHOD

It is important to note that, for the workover and restart of the well, the Company has the following equipment:

- Beam pumping weight of 9 t and 12 t,
- Sucker rods with a diameter of 19 mm, 22 mm, and 25 mm,
- Tubing with a diameter of 73 mm.

This equipment can facilitate the transition to a **subsurface pumping system (SRP)**, which could potentially stabilize production and reduce issues with pump temperature.

Further analysis for the sucker rod pump is done by using the **Qrod 3.1** software package, Echometer company. Table 3 presents the pumping parameters that are used as input data for the **QRod 3.1** software.

Table 3 Input data for a sucker rod pump (SRP)

Pump depth	2090	m
Surface stroke length	2508	mm
Pump diameter	38,1	mm
Tubing outside diameter	73	mm
Tubing inside diameter	62	mm
Tubing pressure	4	bar
Casing pressure	13	bar
Reservoir pressure	80	bar
Productivity index	6.57	m^3/day/bar
Pump volumetric efficiency	80	%
Surface unit efficiency	80	%
Stroke rate	6.55	

The calculation results are presented in Table 4. These results provide valuable insights into the performance and efficiency of the selected pumping method, highlighting key parameters such as production rates, operational efficiency, and potential issues identified during the analysis.

Table 4 Calculation results for the sucker rod pump (SRP)

Rate (100% pump volumetric eff.)	21.9	m^3/d
Rate (80% pump volumetric eff.)	17.5	m^3/d
Rod taper	34.0, 66.0	%
Top steel rod loading	72.8	%
Min API unit rating	320-173-99	
Min NEMA D motor size	8.66	kW
Polished rod power	4.16	kW
TVLoad	6 573	kg
SVLoad	5 038	kg

Figure 4 shows three dynamically updated graphs generated by Qrod 3.1, analyzing the performance of a sucker rod pump system. The "Dynamometer Cards" graph illustrates rod load versus position, providing insights into pump mechanics and efficiency. The "Pump Velocity vs. Position" graph shows plunger velocity changes during the stroke, revealing fluid movement dynamics. The "Torque" graph displays gearbox torque variations with crank angle, highlighting peak loads and counterbalancing effects. This analysis supports the optimization of oil production operations.

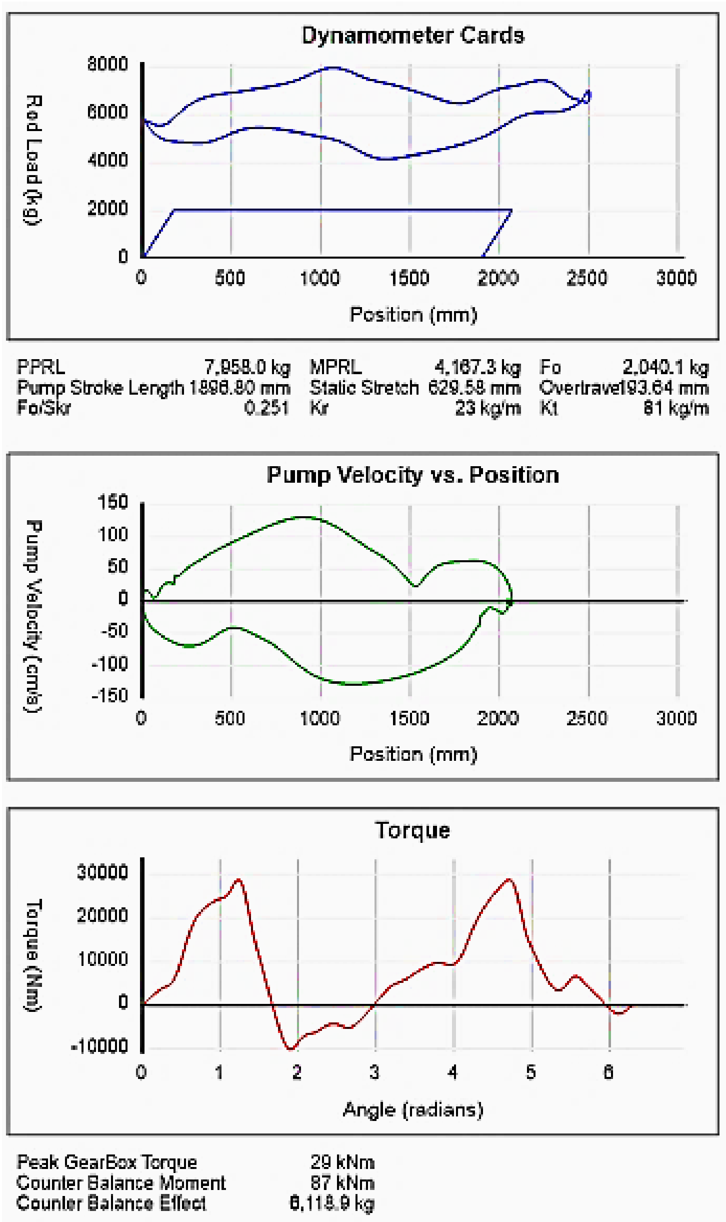

Figure 6 Diagrams of the operational characteristics of a sucker rod pump ("Qrod 3.1.")

To calculate the stability of SRP systems, the methodology involves analyzing key operational parameters such as rod load dynamics, pump velocity profiles, and torque variations, as shown in the provided dynamometer card data. This data is used to assess the pump's ability to handle variations in flow rates and well conditions, ensuring consistent performance under the given operational constraints.

The SRP has been evaluated for flows between:

- **21.9 m³/day at 100% volumetric efficiency**
- **17.5 m³/day at 80% volumetric efficiency**

Given that the fluid flow from the well is 18 m³/day, the pump appears to be suitable for this flow for the following reasons:

- **Efficiency and Flow Adaptability**: The pump is designed to operate close to 18 m³/day (at an efficiency of around 80%). The current flow rate of 18 m³/day is very close to these values, indicating that the pump will function within its design parameters without significant overload issues.
- **Proximity to Maximum Capacity**: The pump is rated for a slightly higher flow (21.9 m³/day), but given that the difference is minimal, it will continue to operate efficiently. Therefore, issues such as insufficient delivery or loss of volumetric efficiency are not expected.

5 CONCLUSION

The choice between sucker rod pumps (SRP) and electric submersible pumps (ESP) application depends on the specific demands of the oil well. SRP systems provide flexibility and resilience in challenging operating conditions, such as high pressures and exposure to corrosive chemicals, making them suitable for complex environments. Conversely, ESP systems offer high efficiency and stability in more consistent operating conditions, ensuring steady production and simpler maintenance.

In wells with low fluid inflow, where ESP systems are applied, intermittent operation is often used to reduce energy costs and extend equipment life. However, ESPs are not designed for intermittent operation, which increases susceptibility to failures, decreases efficiency, and raises maintenance costs. By contrast to that, SRP equipment is available, and trained personnel are on hand for maintenance and management, making the SRP method a more reliable and long-term stable solution for low-inflow wells. It offers higher productivity and lower maintenance costs compared to the intermittent operation mode of ESP systems.

Through an analysis of the ESP and oil well parameters, a significant reduction in fluid inflow into the well was observed.

The primary cause of ESP overheating was insufficient reservoir fluid inflow, leading to reduced fluid circulation around the pump and, therefore, limited motor cooling. In these conditions, the sucker rod pump exhibited significantly better performance compared to the ESP.

Calculation results for the sucker rod pump show operational stability under specific well and fluid conditions.

These results confirm that the SRP provides reliable and efficient operation, which is crucial for optimizing production in complex and demanding conditions. The observed operational stability, confirmed by the calculations, indicates its ability to handle variations in operating conditions and fluid properties effectively, ensuring continuous productivity and minimizing the risk of production interruptions.

In this case, potential limitations of SRP include the ongoing maintenance and the need for periodic upgrades to adapt to changing well conditions or improve efficiency. These requirements can increase operational costs over time and may affect the overall cost-effectiveness of SRP systems. However, in addition to this, in this case, the SRP pump remains a better option both technically and economically.

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REFERENCES

CLEGG, J., BUCARAM, S., and N.W. HEIN, J. (1993). "Recommendations and Comparisons for Selecting Artificial-Lift Methods (includes associated papers 28645 and 29092)." Journal of Petroleum Technology, 45, pp. 1128-1167.

CRNOGORAC, M. P. (2020). Optimisation of the Selection of the Artificial Lift Method of Oil Well Exploitation Using Fuzzy Logic. Doctoral dissertation (PhD), University of Belgrade.

DE LA FONTE, S. S., and SIMONELLI, G. (2017). "Operating Parameters of Electrical Submersible Pump Simulation Using Excel." International Journal of Advanced Research in Science, Engineering and Technology, 4(5), pp. 3890-3896.

DURU, UGOCHUKWU ILOZURIKE, NWANWE, ONYEBUCHI IVAN, NWANWE, CHIBUZO COSMAS, ARINKOOLA, AKEEM OLATUNDE, and CHIKWE, ANTHONY OGBEGBE. (2021). "Evaluating Lift Systems for Oil Wells Using Integrated Production Modeling: A Case Study of a Niger Delta Field." Journal of Petroleum Engineering & Technology, 11(3), pp. 32-48.

FAKHER, S., KHLAIFAT, A., HOSSAIN, M. E., and NAMEER, H. (2021). "A Comprehensive Review of Sucker Rod Pumps' Components, Diagnostics, Mathematical Models, and Common Failures and Mitigations." Journal of Petroleum Exploration and Production Technology, 11(10), pp. 3815-3839.

FLATERN, R. V. (2015). "The Defining Series: Artificial Lift." [Online] SLB. Available from: https://www.slb.com/resource-library/oilfield-review/defining-series/defining-artificial-lift [Accessed 10/15/24].

LADOPOULOS, E. G. (2020). "Is ESP Artificial Lift the Most Convenient Method for Oil & Gas Well Development? What Will Be Next?" Universal Journal of Hydraulics, 8, pp. 1-14.

OKODI, E. (2017). A Comparative Study of Electrical Submersible and Sucker-Rod Pumps for Production Optimization. Research Project, University of Uyo.

PANDIT, AKCHAY L., et al. (2015). "Economic Comparison Between ESP and Rod Pump for Same Rate Wells." In SPE/IATMI Asia Pacific Oil & Gas Conference and Exhibition. Nusa Dua, Bali, Indonesia: Society of Petroleum Engineers.

TAKACS, G. (2017). Electrical Submersible Pumps Manual. 2nd ed. Houston, Texas: Gulf Publishing Company.

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