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Monitoring of Post-Industrial Mining and Chemical Sites in the Context of the Green Transition

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The paper substantiates an approach to digital monitoring of the physicochemical state of post-industrial mining and chemical sites in the context of the green transition and sustainable development. The approach is based on the complementary use of optical sensing, digital image acquisition and processing, and identification of distributed monitoring points. The Rozdil Mining and Chemical Enterprise "Sirka" is considered a case study of a post-industrial site that requires long-term environmental monitoring during reclamation and subsequent management. The potential of optical sensing is analysed as a means of obtaining repeated information on changes in selected physicochemical parameters through changes in the colour or other optical characteristics of sensitive elements. The proposed concept includes digital identification of sensor tags and association of optical responses with specific monitoring points and contextual information. Optical monitoring is considered a complementary tool to conventional laboratory and instrumental methods, rather than a replacement for them. The approach can provide a basis for the spatially distributed collection of structured environmental data and support the assessment of environmental changes, reclamation planning, and sustainable management of post-industrial territories. Further research should focus on the calibration of optical sensing elements, the standardization of image acquisition, and validation under real-world environmental conditions.

Keywords: post-industrial territories, mining and chemical enterprises, environmental monitoring, digital monitoring, optical sensing, colorimetric sensing, green transition, sustainable development.

Introduction

The reclamation of post-industrial mining territories is an important component of sustainable land management and the transition towards a green economy. Former mining and chemical sites may remain sources of environmental risk due to accumulated waste, disturbed soils, altered hydrological conditions, and residual contamination. Their rehabilitation, therefore, requires not only restoration measures but also long-term assessment of environmental changes and the effectiveness of reclamation activities (Worlanyo & Jiang, 2021; Martins et al., 2020; Harries et al., 2024).

The Rozdil Mining and Chemical Enterprise "Sirka" is a representative post-industrial mining and chemical site in Ukraine. Its long-term operation resulted in substantial landscape transformation and accumulation of industrial waste. Previous studies have reported changes in surface- and groundwater quality, as well as soil degradation, in post-industrial mining areas (Pohrebennyk et al., 2019; Bernatska et al., 2023). Such conditions require monitoring approaches that provide spatially and temporally relevant information during reclamation and subsequent management of the territory.

Conventional monitoring based on field sampling, laboratory analysis, and instrumental measurements remains essential for quantitative environmental assessment. However, repeated measurements at numerous distributed locations can be resource intensive. This creates a need for complementary approaches that can provide operational information on environmental changes. Digital technologies offer opportunities to combine sensing, image acquisition, automated processing, identification of observation points, and structured storage of monitoring data.

Optical sensing is a promising basis for such approaches because changes in environmental conditions can be represented by changes in the colour or other optical characteristics of a sensitive element. Low-cost and portable colorimetric sensors have been widely investigated for environmental analysis, while digital imaging provides a means of recording and processing optical responses outside conventional laboratory instrumentation (Alberti et al., 2020; Caroleo et al., 2022; Kant et al., 2023). The use of an external imaging device also enables separation of the sensing element from the measurement and data-processing system, which may be advantageous for distributed monitoring.

For practical digital monitoring, the optical response should be linked to the corresponding sensor, observation point, monitored parameter, and observation history. The combination of optical sensor tags with digital identification technologies can provide such a link and lay the foundation for structured, spatially distributed environmental observations. In this context, optical monitoring is considered not as a replacement for laboratory and instrumental analyses but as a complementary source of repeated information that can support environmental management and reclamation planning.

Therefore, the purpose of this study is to substantiate an approach to digital monitoring of the physicochemical state of post-industrial mining and chemical sites in the context of the green transition and

sustainable development, with a focus on the potential of optical sensing methods. The Rozdil Mining and Chemical Enterprise “Sirka” is considered a case study.

Study Area and Research Methods

The study focuses on the territory of the former Rozdil Mining and Chemical Enterprise “Sirka”, located in the Lviv Region of western Ukraine. The enterprise operated from 1956 to 1996 and was associated with the extraction and processing of sulphur-containing raw materials. During the operational period, significant volumes of industrial waste accumulated within the territory, including sulphur-containing materials, flotation tailings, phosphogypsum, recycled water sediments, tars, and other waste materials. Following the cessation of production, the territory acquired the characteristics of a post-industrial landscape with disturbed soils, altered hydrological conditions, and a number of potentially hazardous environmental features.

Previous investigations of the territory and other post-industrial mining areas have identified changes in surface- and groundwater quality and degradation of soil properties. In particular, the occurrence of elevated concentrations of individual chemical components in environmental media indicates the need for long-term observation of physicochemical changes during reclamation and subsequent management of the territory (Pohrebennyk et al., 2019; Bernatska et al., 2023). These characteristics make the “Sirka” site suitable as a case study for considering approaches to distributed digital environmental monitoring.

The monitoring concept considered in this study is intended for environmental components and observation points where changes in selected physicochemical parameters can be associated with a measurable optical response. The proposed approach does not assume replacement of existing laboratory and instrumental monitoring. Instead, it is considered as an additional layer of observation that can provide repeated information on environmental changes at selected locations.

The research is based on a conceptual and technological analysis of the potential application of optical sensing methods for digital monitoring of post-industrial mining and chemical territories. The proposed approach combines four principal components: an optical sensing element, digital image acquisition, automated processing of the optical signal, and digital identification of the observation point.

Results and Discussion

The general monitoring workflow includes the following stages:

1. Selection of the monitoring parameter and observation point. A physicochemical parameter relevant to the environmental condition of the territory is selected, and a corresponding monitoring location is defined.

2. Optical sensing. A passive optical sensing element is placed at the selected observation point. A change in the monitored environmental parameter is associated with a change in the optical characteristics of the sensing element, such as colour or spectral response.

3. Digital image acquisition. The optical state of the sensing element is recorded using a digital camera, smartphone, or another suitable imaging device. The sensing element does not require a direct electrical connection to the image acquisition device.

4. Digital identification. A sensor tag can be combined with a QR code or another digital identifier. The identifier can contain information about the monitoring point, sensor, monitored parameter, or other metadata required for interpretation of the measurement.

5. Image processing and optical parameter extraction. The acquired image is processed using computer-vision and image-analysis techniques. Depending on the sensor design, the processing may include image cropping, geometric correction, noise reduction, colour-space transformation, white-balance correction, and extraction of colour or spectral characteristics from the sensing area.

6. Association of the optical response with environmental information. The extracted optical characteristics are linked to the identifier and corresponding monitoring point, creating a structured digital observation.

7. Integration into a monitoring system. Repeated observations can be accumulated in a digital database or information system, enabling comparison of measurements over time and between spatially distributed monitoring points.

Attention is given to the factors that may influence the reliability of optical measurements. These include illumination conditions, camera characteristics, observation geometry, white balance, image noise, and the optical properties of the sensor surface. Standardisation of image acquisition and appropriate calibration are therefore considered necessary for obtaining comparable measurements.

The methodological approach assumes that optical sensing should be used as a complementary monitoring technique. Laboratory analysis and established instrumental methods remain necessary for quantitative verification and detailed characterisation of environmental samples, whereas optical monitoring can provide additional repeated observations and support early identification of changes in the monitored condition.

The applicability of the proposed approach to the "Sirka" site is assessed conceptually by considering the characteristics of the post-industrial territory, the need for distributed environmental observation, and the potential of optical sensing and digital image processing to support monitoring during reclamation and subsequent sustainable management.

The analysis of the environmental characteristics of the Rozdil Mining and Chemical Enterprise "Sirka" and the potential of optical sensing methods indicates that digital optical monitoring can be considered as a complementary component of environmental management of post-industrial territories. The main advantage of the proposed approach is the possibility of combining a passive sensing element, digital identification, image-based measurement, and structured storage of observations within a single monitoring workflow.

The reliability of optical monitoring remains an important methodological issue. Optical measurements can be affected by illumination, camera characteristics, observation distance and angle, surface properties, white balance, and image-processing parameters. Consequently, practical implementation requires standardised image acquisition procedures, calibration of sensor responses, and validation against conventional instrumental or laboratory measurements. These requirements are particularly important when optical measurements are intended for quantitative assessment rather than simple detection of changes.

The proposed approach should therefore be regarded as complementary to, rather than a replacement for, established environmental monitoring techniques. Laboratory analyses remain necessary for determining the detailed chemical composition of environmental media and for regulatory assessment. Optical monitoring can provide more frequent observations between laboratory measurements, support the identification of changes requiring further investigation, and facilitate the spatial distribution of monitoring points.

From the perspective of the green transition, the integration of optical sensing into digital environmental monitoring can contribute to more information-based management of post-industrial territories. The availability of spatially and temporally structured environmental data can support prioritisation of reclamation measures, assessment of changes during restoration, identification of areas requiring additional investigation, and subsequent evaluation of the effectiveness of rehabilitation measures.

Conclusions

A conceptual approach to digital monitoring of the physicochemical state of post-industrial mining and chemical sites in the context of the green transition and sustainable development has been proposed. The approach combines passive optical sensing, digital image acquisition and processing, identification of monitoring points, and structured storage of environmental observations.

The analysis demonstrates that optical sensing methods can serve as a complementary component of environmental monitoring systems for post-industrial territories. Their potential advantage is the possibility of recording changes in the optical response of a sensing element using an external imaging device without requiring a direct electrical connection at the sensing point. This creates opportunities for distributed observations in locations where conventional electrical sensors may be technically inconvenient.

The integration of optical sensor tags with digital identification technologies, such as QR codes, provides a means of associating an optical measurement with a specific monitoring point, monitored parameter, and additional contextual information. Combined with image-processing techniques, this approach can form a basis for collecting spatially and temporally structured environmental data.

For the Rozdil Mining and Chemical Enterprise "Sirka", the proposed approach can complement conventional laboratory and instrumental monitoring during reclamation and subsequent management of the post-industrial territory. Its potential application includes repeated observation of selected physicochemical changes in environmental components and support for the identification of areas requiring further investigation.

From the perspective of the green transition and sustainable development, digital optical monitoring can contribute to more informed management of disturbed territories by providing additional operational information on environmental changes. Further research should focus on the selection and calibration of optical sensing elements for specific physicochemical parameters, standardisation of image acquisition conditions, validation against laboratory and instrumental measurements, and experimental testing under real environmental conditions at post-industrial sites.

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