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ОГЛЯД КРИСТАЛОГРАФІЧНИХ БАЗ ДАНИХ ДЛЯ НАВЧАННЯ МАЙБУТНІХ ФАХІВЦІВ У ГАЛУЗІ НАНОМАТЕРІАЛОЗНАВСТВА В УМОВАХ АСИНХРОННОГО НАВЧАННЯ

REVIEW OF CRYSTALLOGRAPHIC DATABASES FOR EDUCATING FUTURE SPECIALISTS IN NANOMATERIALS SCIENCE IN ASYNCHRONOUS LEARNING ENVIRONMENTS

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ABSTRACT

This article explores crystallographic databases as transformative resources for nanomaterials science education, focusing on Ukraine's unique challenges and opportunities. Amidst an evolving educational landscape that increasingly demands flexibility and resilience, this study underscores digital tools' critical role in facilitating synchronous and asynchronous learning formats. By meticulously analyzing four prominent crystallographic databases—The Cambridge Crystallographic Data Centre, the Crystallography Open Database, the Inorganic Crystal Structure Database, and the Materials Project—the research offers a comprehensive evaluation based on several critical criteria: accessibility and user interface, richness, and relevance of content, potential for integration into educational programs, support for research and innovation, and considerations regarding costs and licensing. Through these criteria, the article presents an insightful comparative analysis, revealing each database's strengths and areas for improvement in supporting educational endeavors in nanomaterials science. A focal point of the study is a task example crafted using the Materials Project database, aimed at illustrating the practical application of these resources in an asynchronous learning context. This example serves as a guide for educators seeking to incorporate digital tools into their curriculum and as a model for engaging students in hands-on, exploratory learning. The culmination of this research is a discussion that accentuates the pressing need for developing adaptable educational formats in Ukraine, highlighting a significant gap in specialized training methods for aspiring nanomaterials scientists. The article concludes with strategic recommendations for the effective use of crystallographic databases in educational settings, advocating for their integration as a means to enrich nanomaterials science education. In doing so, it posits that such digital resources are indispensable in equipping future specialists with the knowledge and skills necessary for innovation, thereby contributing to Ukraine's technological progress and competitiveness in the global arena.

Key words: *nanomaterials science education, crystallographic databases, asynchronous learning, synchronous learning, digital education tools, Ukraine, educational technology, Materials Project, CCDC, COD, ICSD.*

Introduction

In a rapidly changing world, where wars, technological shifts, and global epidemics shape new challenges and opportunities, the education and training of specialists in high-tech fields take on special significance [1, 2]. The modern world has encountered a critical need for specialists who possess

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advanced knowledge and skills in nanotechnology, capable of developing cutting-edge materials and technologies and effectively implementing them in various aspects of life [7]. This is particularly true for Ukraine, which finds itself in dire need of qualified personnel and faces unprecedented challenges related to the war and its consequences for education, industry, energy, and other sectors [8, 10].

The field of nanotechnology is constantly evolving, offering novel solutions for a wide range of applications, from medicine and electronics to materials science and energy [3, 12]. However, such rapid development requires universities to continually update their curricula, adapting them to modern technological demands and market needs [4].

The educational process for preparing specialists in nanotechnology imposes high demands. It must include not only theoretical knowledge in physics, chemistry, and materials science but also practical skills in working with specialized software for modeling and analyzing nanostructures. The peculiarity of such training lies in using large data sets and complex computing systems for research in this field [11].

Developing effective educational programs in nanotechnology also requires the involvement of highly qualified specialists, access to advanced scientific laboratories and equipment, and integration with the latest research and developments in this area. This ensures that students acquire the necessary theoretical knowledge and practical skills, which are critically important for their future professional activity.

One of the critical aspects of modern training for specialists in nanomaterials science is the development of special qualification skills that meet the labor market demands [9]. In a world of rapid technological progress and continuous evolution of scientific knowledge, these skills become decisive for a successful career.

The ability to learn quickly and adapt to new technologies is crucial for specialists aiming to stay at the forefront of scientific and technical progress. In a world where discoveries and technologies emerge quickly, quickly assimilating new knowledge and tools is critical. This applies to fundamental scientific knowledge and practical skills in working with the latest equipment, software, and research methodologies [13].

Critical thinking skills are an integral part of the training of specialists, allowing them to effectively analyze information, identify connections between different data, and critically evaluate the results of experiments and developments. When it is necessary to make complex decisions based on a limited set of data or under time pressure, the ability to think critically and make reasoned conclusions becomes crucial.

The development of these special qualification skills requires educational programs not just the transfer of knowledge but also the creation of conditions for the practical application of this knowledge in various situations. This can include project work, case methods, working on real scientific problems, and internships in the industry. Such an approach helps students not only to acquire the necessary theoretical knowledge but also to develop important professional skills, preparing them for effective work in the rapidly changing world of nanotechnology. A modern specialist in nanomaterials science must undoubtedly possess a wide range of knowledge and skills, including the ability to use specialized software and work with databases. These tools are critically important for analyzing, modeling, and designing nanomaterials and nanostructures, allowing scientists and engineers to predict material properties, optimize their applications, and develop new products [5].

However, despite the significant role of these technologies in modern science and engineering, the issue of their teaching and application in the educational process has received insufficient attention. In particular, there has been little research on effective ways to integrate software and databases into the educational process, especially in distance education, which includes synchronous and asynchronous learning forms [6].

The integration of these tools into synchronous and asynchronous learning formats can include the use of online laboratories, virtual simulations, databases for independent study and research, and the development of interactive tasks and projects that allow students to practically apply the knowledge and skills acquired in real research scenarios.

In summary, the literature review highlights the complexity and multifaceted nature of training specialists in nanotechnology. This field requires a comprehensive approach to learning that combines deep theoretical knowledge, the ability to apply specialized software, process large volumes of data, and develop the necessary qualification skills for a successful career in this rapidly growing field.

Our article aims to evaluate the potential of crystallographic databases as educational tools in nanomaterials science, focusing on their application in asynchronous learning environments within Ukraine. This analysis aims to highlight how these databases can support the educational process, enhance the learning experience for students, and address the current need for innovative and flexible learning formats. By providing insights into the accessibility, content, and integration of these databases into educational programs, the article seeks to offer practical recommendations for educators and policymakers. Ultimately, it endeavors to contribute to advancing nanomaterials science education, preparing future specialists to meet the demands of technological innovation and research in a rapidly evolving digital educational landscape.

Methodology. Our research analyzed crystallographic databases comprehensively to evaluate their utility in nanomaterials science education,

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specifically within the Ukrainian context. Our methodology involved a detailed exploration of four major databases: The Cambridge Crystallographic Data Centre, the Crystallography Open Database, the Inorganic Crystal Structure Database, and the Materials Project. These were selected based on their relevance, data richness, and diverse applications in nanomaterials science.

We employed criteria to assess each database, focusing on accessibility and user interface, content richness and relevance, educational program integration, research and innovation support, and costs and licensing. This multifaceted approach allowed us to comprehensively understand each database's strengths and limitations in supporting both synchronous and asynchronous learning formats.

Following the evaluation, we developed a task example using the Materials Project database to illustrate how these resources can be practically applied in educational settings, particularly asynchronous learning. The task was designed to enhance students' learning experience in studying A3B5 semiconductors, demonstrating the databases' practical applicability in real-world educational scenarios.

We emphasized the gap in training methods for future nanomaterials science specialists and proposed recommendations for integrating crystallographic databases into educational programs. This sequential approach, from database analysis to practical application and policy recommendations, provided a holistic view of the potential of these digital tools in advancing nanomaterials science education in Ukraine.

Analysis of Crystallographic Databases

Cambridge Crystallographic Data Centre (CCDC)

The Cambridge Crystallographic Data Centre is a pivotal resource in the crystallography community, underpinning educational and research endeavors in nanomaterials science. Renowned for its comprehensive collection of crystal structure data, CCDC facilitates a deeper understanding and exploration of material properties at the molecular level.

The CCDC platform is designed with a focus on user accessibility. It features an intuitive interface catering to seasoned researchers and students new to the field. Access to data is streamlined through various search functions and filters, making it straightforward for users to locate specific datasets. Integrating visual tools further enhances the learning experience, allowing users to visualize complex crystal structures easily.

With a vast repository that spans decades of research, the CCDC boasts an unparalleled richness of content. It includes data from thousands of published sources, covering various materials from organic compounds to complex biomolecules. This extensive database is regularly updated, ensuring its relevance and utility for ongoing research projects and educational purposes.

The CCDC's potential for integration into educational programs is significant. It offers specialized resources for teaching, including case studies and tutorial guides that facilitate the incorporation of crystallographic data into coursework and research projects. These resources are invaluable for asynchronous learning environments, where students may be navigating the material independently.

The CCDC is indispensable for innovation in nanomaterials science as a research tool. It provides advanced functionalities for analyzing crystal structures, predicting material interactions, and designing new materials. Researchers can leverage the CCDC's computational tools for various applications, from drug discovery to developing novel nanomaterials.

While the CCDC offers specific free resources to the academic community, comprehensive access to its databases and tools may require a subscription or licensing agreement. Institutions typically bear the cost, providing their members with wide-ranging access. For individual researchers and smaller institutions, the cost factor may necessitate careful planning and budgeting to ensure access to these valuable resources.

The Cambridge Crystallographic Data Centre emerges as a foundational pillar of crystallographic databases, offering extensive resources supporting nanomaterials science's educational and research facets. Its contribution to the field is underscored by its user-friendly platform, rich content, and commitment to facilitating research and innovation. As we continue to navigate the complexities of asynchronous learning, the CCDC's resources provide a crucial bridge between traditional educational methods and the demands of modern scientific inquiry.

Crystallography Open Database (COD)

The Crystallography Open Database (COD) distinguishes itself as an essential, publicly accessible repository of crystal structures. Its open-access model supports the democratization of scientific information, making it an invaluable asset for educators, students, and researchers worldwide.

Accessibility is a hallmark of the COD, and it is freely available to users worldwide without subscription or membership fees. This open-access approach ensures that valuable crystallographic data is available to anyone with internet access, promoting inclusivity in scientific research and education. The user interface is straightforward, facilitating easy navigation and data retrieval even for those new to the field of crystallography.

The COD boasts a vast and growing collection of crystallographic entries, covering a broad spectrum of materials from organics and inorganics to metals and biomolecules. This repository is enriched through contributions from the global scientific community, ensuring a continually updated and diverse dataset. The relevance of the COD's content to various research and educational needs makes it a versatile tool in the study and application of nanomaterials science.

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The COD is exceptionally well-suited for integration into educational programs, particularly in asynchronous learning environments, given its open-access nature. Educators can easily incorporate COD resources into their teaching materials, assignments, and projects, enabling students to explore real-world data and engage in hands-on learning experiences. The availability of such a comprehensive dataset supports a wide range of educational objectives, from introductory courses to advanced research projects.

For researchers in nanomaterials science, the COD offers a rich dataset for analysis, hypothesis testing, and material discovery. Its open-access model encourages collaborative research efforts and fosters innovation by providing a shared data exchange and analysis platform. The COD's commitment to maintaining a comprehensive and up-to-date database makes it a vital resource for advancing the frontiers of science.

The COD's open-access policy means that its resources are available without cost, removing financial barriers to information and making it a precious resource for institutions with limited funding. This approach aligns with the broader scientific community's move towards open science, ensuring that crystallographic data can be freely accessed and utilized worldwide for educational and research purposes.

In conclusion, the Crystallography Open Database stands out for its commitment to making crystallographic data freely accessible to all. Its extensive and diverse collection of crystal structures, combined with the ease of access and integration into educational programs, positions the COD as a critical resource in the landscape of nanomaterials science education and research. As the field continues to evolve, the COD's open-access model serves as a blueprint for future scientific databases, promoting transparency, collaboration, and innovation in the global scientific community.

Inorganic Crystal Structure Database (ICSD)

The Inorganic Crystal Structure Database (ICSD) is a specialized repository focused on the crystal structures of inorganic compounds. It is a pivotal resource for researchers and educators in nanomaterials science, particularly those engaged with inorganic materials.

Access to the ICSD is typically provided through institutional subscriptions, which offer comprehensive access to its database for affiliated researchers and students. The platform is designed with a professional and intuitive interface, facilitating efficient search and retrieval of crystallographic data. The ICSD's focus on user experience ensures that users can navigate the database effectively, with various search filters and tools available to refine and target their queries.

Dedicated exclusively to inorganic compounds, the ICSD houses an extensive collection of crystallographic entries, making it the largest database. It covers a broad spectrum of inorganic materials, from simple salts to complex minerals and synthetic compounds. This focus ensures that the database remains highly relevant to those researching inorganic nanomaterials, offering detailed structural data that underpin the development and characterization of these materials.

While the ICSD's subscription model may limit direct access for individual students, its wealth of data and analytical tools presents significant opportunities for integration into educational programs at the institutional level. Educators can utilize the database to teach material science principles, crystallography, and the properties of inorganic materials, enhancing the depth and breadth of their curriculum. Additionally, the ICSD can support student research projects, providing a solid foundation for exploring inorganic material structures and their applications.

For the research community, the ICSD offers an indispensable tool for discovering and designing new inorganic materials. Its comprehensive dataset enables researchers to perform comparative analyses, identify structural patterns, and predict material properties. The ICSD's support for innovation extends to various fields, including catalysis, energy storage, and semiconductors, where inorganic materials play a critical role.

The ICSD is accessible through a subscription model, which may vary in cost depending on the institution's size and type. While this may pose a barrier to individual users without institutional support, the investment is justified by the database's unmatched depth and scope in the realm of inorganic crystal structures. For academic institutions, the subscription ensures that students and researchers have access to a vital resource supporting educational and research objectives.

In summary, the Inorganic Crystal Structure Database emerges as an essential tool for the nanomaterials science community, especially for those focused on inorganic compounds. Its targeted collection and robust search and analysis tools make the ICSD a cornerstone for research and education in inorganic materials science. As we advance towards more specialized and application-driven research, the ICSD's role in supporting discovery and innovation in inorganic materials will likely grow, underscoring the importance of ensuring broad access to this invaluable resource.

Materials Project

The Materials Project is a pioneering platform in materials science research, leveraging advanced computational algorithms and vast databases to predict material properties and discover new materials. This resource is precious for those engaged in the study and application of nanomaterials, offering insights that span the breadth of materials science.

Accessibility is at the core of the Materials Project's mission, with the platform offering free access to a substantial portion of its database to

ICV 2022: 80.27
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registered users. This approach democratizes access to cutting-edge materials science data and tools, fostering a wide-reaching community of researchers and educators. The user interface of the Materials Project is modern and user-friendly, designed to facilitate easy navigation and efficient data retrieval, even for those with limited computational experience.

The Materials Project distinguishes itself with its focus on computational materials science. It offers a vast array of data on material properties predicted using quantum mechanical simulations. This includes information on thousands of materials, from metals and ceramics to polymers and semiconductors. The relevance of this content to nanomaterials science is profound, providing a predictive lens through which new materials can be explored and existing materials can be better understood.

The Materials Project is well-suited for integration into educational programs, particularly in disciplines focused on materials science and engineering. It provides educators with a rich resource for developing course materials, including the latest in computational materials science. Moreover, the platform's tools and data can create interactive assignments and projects that engage students in discovery and innovation. It is an excellent fit for asynchronous learning environments where students may be working independently.

As a hub for research and innovation, the Materials Project offers unparalleled resources for exploring and developing new materials. Its predictive models and databases are instrumental in identifying materials with desired properties, thereby accelerating the materials design process. For researchers in nanomaterials science, the platform's ability to predict properties like stability, electronic structure, and reactivity is invaluable, supporting efforts ranging from energy storage solutions to novel nanoelectronic devices.

The Materials Project provides free access to a significant portion of its resources, although some advanced features and capabilities may require additional access permissions or collaborations. This model supports widespread use by individuals and institutions alike, ensuring that the materials science community has access to these computational tools and databases.

In summary, the Materials Project represents a revolutionary approach to materials science, offering a computational platform that supports educational and research goals in nanomaterials science. Its commitment to accessibility, combined with the depth and relevance of its data, makes it an indispensable resource for those looking to explore the frontiers of materials science. As we continue to push the boundaries of what is possible with nanomaterials, the Materials Project's predictive power and collaborative potential will undoubtedly play a critical role in shaping the future of the field.

Comparative Analysis of Crystallographic Databases for Synchronous and Asynchronous Learning in Nanomaterials Science

Integrating crystallographic databases into distance learning, particularly within synchronous and asynchronous formats, is pivotal for advancing education in nanomaterials science. The Cambridge Crystallographic Data Centre (CCDC), the Crystallography Open Database (COD), the Inorganic Crystal Structure Database (ICSD), and the Materials Project each offer unique advantages and face specific challenges in this context. A comparative analysis reveals how these resources can be optimally utilized to enhance educational outcomes in the field.

Accessibility and User Interface:

- CCDC and ICSD offer user-friendly interfaces but require institutional subscriptions, which might limit access in specific scenarios. Their professional layouts are well-suited for synchronous learning environments where instructors can guide students through navigation and usage.
- COD, with its open-access model, stands out for asynchronous learning, offering unrestricted access to its database, thus facilitating independent study.
- The Materials Project also promotes wide accessibility with free registration. Its intuitive design and extensive online tutorials support both synchronous and asynchronous learning.

Content Richness and Relevance:

- CCDC provides a comprehensive collection of organic and inorganic crystal structures, supporting a broad spectrum of research and learning applications in nanomaterials science.
- COD offers a vast, open-access repository of crystallographic data, making it an invaluable resource for students and researchers exploring various materials.
- ICSD focuses on inorganic compounds, making it particularly relevant for courses and research in inorganic materials science.
- The Materials Project excels in computational predictions of material properties, offering unique insights into materials design and discovery, beneficial for advanced students and research projects.

Integration with Educational Programs:

- CCDC and ICSD's structured databases and analytical tools can be seamlessly integrated into curriculum design, particularly for institutions that can afford the subscription costs. They are instrumental in synchronous settings where instructors can incorporate database exploration into their lessons.
- COD and The Materials Project, with their open-access policies, are excellent for asynchronous courses. They allow students to explore materials data independently and at their own pace. Their extensive data and tools also support project-based learning and independent research.

ICV 2022: 80.27
DOI 10.32782/2412-9208-2024-1

Support for Research and Innovation:

- All databases significantly contribute to research and innovation in nanomaterials science. CCDC and ICSD offer detailed crystallographic data critical for materials characterization and development.
- COD provides a broad platform for comparative studies and materials exploration.
- The Materials Project stands out for its predictive capabilities, which are driving the discovery of new materials and applications.

Costs and Licensing:

- The cost and licensing structure of CCDC and ICSD may pose barriers to individual access, especially in asynchronous learning environments where students are encouraged to explore resources independently.
- COD and The Materials Project, being freely accessible, remove these barriers, democratizing access to crystallographic information and computational materials science tools.

In conclusion, each crystallographic database has strengths and limitations in the context of distance learning in nanomaterials science. For synchronous formats, databases like CCDC and ICSD, with their comprehensive collections and analytical tools, can enhance instructor-led sessions. In contrast, COD and The Materials Project are particularly well-suited to asynchronous learning environments, promoting independent exploration and research. The choice of database for a particular educational setting will depend on the specific needs of the curriculum, the focus of the study, and the accessibility of the resource to the institution and its students. By leveraging these resources effectively, educators can significantly enrich the learning experience and outcomes for students in nanomaterials science.

Asynchronous Learning Task: Exploring A3B5 Semiconductors Using the Materials Project

Below, we present a detailed example of an asynchronous learning task designed to engage students in the practical aspects of nanomaterials science. This task leverages the Materials Project platform to explore the properties of A3B5 semiconductors, a class of materials with significant applications in electronics and optoelectronics. Through this exercise, students will deepen their understanding of these materials and develop essential research skills, including data analysis, critical thinking, and independent inquiry.

This specific example of a task is crafted to be both accessible and challenging, providing students with a clear framework for exploration while encouraging them to take ownership of their learning process. By completing this task, students will gain valuable experience in navigating one of the most comprehensive materials science databases available today, applying their theoretical knowledge to real-world materials, and articulating their findings in a structured report.

Objective: This task is designed for students to gain hands-on experience with the Materials Project platform, focusing on exploring and analyzing the properties of A3B5 semiconductors. Through this asynchronous learning activity, students will develop their skills in navigating a central crystallographic database, applying theoretical knowledge to practical examples, and independently researching advanced materials.

Background: A3B5 semiconductors have unique electronic and optical properties and are crucial in various applications, including LEDs, laser diodes, and high-speed electronic devices. Understanding these materials' crystal structures and properties is essential for future specialists in nanomaterials science.

Task Description

1. Registration and Orientation:

- Register for a free account on the Materials Project website if you haven't already.
- Familiarize yourself with the platform's interface and resources available. Focus on the tutorials section to learn how to search for materials and analyze their properties.

2. Research Phase:

- Use the Materials Project database to search for A3B5 semiconductors. Identify the compound's general characteristics and common examples (e.g., GaAs, InP).
- Select two A3B5 semiconductors of interest. For each selected material, retrieve the following information:
- Crystal structure and space group
- Lattice parameters
- Band gap energy
- Electron mobility (if available)
- Any available data on optical properties

3. Analysis and Comparison:

- Compare the properties of the two selected A3B5 semiconductors. Discuss how the differences in their crystal structures might influence their electronic and optical properties.
- Utilize the Materials Project's tools for further analysis, such as band structure plots or density of states (DOS) diagrams, to enrich your comparison.

4. Application Discussion:

- Based on your findings, speculate on the potential applications of each semiconductor material. Consider the roles of band gap energy and electron mobility in determining their suitability for specific devices or technologies.

5. Reflection:

- Reflect on your experience using the Materials Project platform. Discuss any challenges you encountered and how you overcame them.

ICV 2022: 80.27
DOI 10.32782/2412-9208-2024-1

- Evaluate how the platform's resources and tools have contributed to your understanding of A3B5 semiconductors and their applications.

Deliverables

Prepare a report detailing your research, analysis, and reflections. The report should include:

- An introduction to A3B5 semiconductors and their importance in nanomaterials science.
- A summary of the properties and potential applications of the two materials you researched.
- Screenshots or figures from the Materials Project to illustrate your findings.
- A discussion section that includes your comparison of the two materials and reflections on using the Materials Project.

Submission:

- Submit your report through the learning management system (LMS) by the deadline specified by your instructor. Ensure your submission is well-organized, clearly written, and includes all required sections.

Evaluation Criteria

- Your submission will be evaluated based on the thoroughness of your research, the clarity and depth of your analysis and comparison, the relevance and feasibility of the discussed applications, and your reflection on the learning process.

This task is designed to encourage independent exploration and critical thinking, essential skills for future specialists in nanomaterials science. By engaging with the Materials Project, students will deepen their understanding of A3B5 semiconductors and develop valuable research skills applicable to various materials science challenges.

Discussion

In Ukraine's current educational and socio-political climate, the development of synchronous and asynchronous forms of education has transitioned from a mere convenience to an essential need. The country's challenges underscore the importance of establishing flexible and resilient educational frameworks capable of adapting to various circumstances. This need is particularly acute in advanced and specialized fields like nanomaterials science, which play a critical role in technological advancement and national development.

Despite the evident demand, there is a notable scarcity of tailored training methods and resources for future specialists in nanomaterials science within these flexible learning formats. Traditional educational materials and methods often do not suffice for the requirements of remote and asynchronous learning environments, impeding student progress and the country's capacity to innovate and compete globally.

The analysis of crystallographic databases presented in this article emerges as a crucial initiative to bridge this educational gap. Databases such as The Cambridge Crystallographic Data Centre, the Crystallography Open Database, the Inorganic Crystal Structure Database, and the Materials Project provide extensive resources for exploring, analyzing, and understanding materials at an atomic and molecular level, which is indispensable for studying nanomaterials science.

Several recommendations are put forward to effectively incorporate these databases into synchronous and asynchronous learning environments. First, it's essential to weave database navigation and data analysis skills into the curriculum, enabling students to undertake projects requiring database utilization independently. Interactive learning activities designed around database resources can enhance engagement, especially in asynchronous settings. Collaborative projects that involve research using these databases can foster teamwork skills in both learning formats. Assigning real-world problem-solving tasks that rely on database data and tools can bridge academic learning with practical applications. Additionally, providing educators with the necessary training and support to use these databases proficiently will enable them to integrate these tools effectively into their teaching practices. Finally, ensuring all students have equal access to these databases by securing institutional subscriptions and promoting open-access resources is fundamental for equitable learning opportunities.

Adhering to these strategies can substantially improve Ukraine's educational offerings in nanomaterials science, preparing a new generation of specialists with the knowledge and skills for innovation. Leveraging crystallographic databases in education enriches the learning experience and aligns with the global shift towards more digital and adaptable educational environments.

The exploration of crystallographic databases in nanomaterials science education opens avenues for further research, particularly in developing more engaging and interactive learning modules. Future studies could also assess the long-term impact of these digital tools on student outcomes and innovation capabilities.

Conclusions

This analysis underscores the pivotal role of crystallographic databases in enhancing nanomaterials science education within Ukraine's evolving educational landscape. Educators can offer more dynamic and comprehensive educational experiences by integrating these resources into synchronous and asynchronous learning formats. These databases facilitate a deeper understanding of material properties at the molecular level and equip students with the practical skills necessary for research and innovation in nanomaterials science. Moving forward, adopting and effectively using such digital tools will be crucial in preparing future specialists to meet

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the challenges and opportunities in nanomaterials science, contributing significantly to Ukraine's technological advancement and competitiveness on the global stage.

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АНОТАЦІЯ

Ця стаття присвячена дослідженню кристалографічних баз даних як трансформаційних ресурсів для наукової освіти з наноматеріалів, зосереджуючись на унікальних викликах і можливостях в Україні. Серед освітнього середовища, що розвивається, яке все більше вимагає гнучкості та стійкості, це дослідження підкреслює критичну роль цифрових інструментів у сприянні синхронним і асинхронним форматам навчання. Ретельно проаналізувавши чотири відомі кристалографічні бази даних — The Cambridge Crystallographic Data Centre, the Crystallography Open Database, the Inorganic Crystal Structure Database, and the Materials Project — дослідження пропонує комплексну оцінку на основі кількох критичних критеріїв: доступність та інтерфейс користувача, насиченість і актуальність змісту, потенціал для інтеграції в освітні програми, підтримка досліджень та інновацій, а також міркування щодо вартості та ліцензування. За допомогою цих критеріїв стаття представляє проникливий порівняльний аналіз, виявляючи сильні сторони кожної бази даних і області, які потребують покращення в підтримці освітніх зусиль у галузі науки про наноматеріали. Основною темою дослідження є приклад завдання, створений з використанням бази даних Materials Project, який має на меті проілюструвати практичне застосування цих ресурсів у контексті асинхронного навчання. Цей приклад служить посібником для викладачів, які прагнуть включити цифрові інструменти в свої навчальні програми, і як модель для залучення студентів до практичного дослідницького навчання. Кульмінацією цього дослідження *є дискусія, яка підкреслює нагальну потребу в розробці адаптованих освітніх форматів в Україні, висвітлюючи значну прогалину в спеціалізованих методах навчання для початківців вчених у галузі наноматеріалів. Стаття завершується стратегічними рекомендаціями щодо ефективного використання кристалографічних баз даних в навчальних закладах, виступаючи за їх інтеграцію як засіб для збагачення наукової освіти з наноматеріалів. Таким чином, йдеться про те, що такі цифрові ресурси є незамінними для забезпечення майбутніх спеціалістів знаннями та навичками, необхідними для інновацій, сприяючи таким чином технологічному прогресу та конкурентоспроможності України на світовій арені.*

Ключові слова*: наноматеріалознавча освіта, кристалографічні бази даних, асинхронне навчання, синхронне навчання, засоби цифрової освіти, Україна, освітні технології, Materials Project, CCDC, COD, ICSD.*

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