Pedagogical Valences of Computer-Assisted Training in the context of Adaptive Ecological Management of Protected Areas

MA stud. **Ioana-Elisabeta CIORUȚA**[1,2], PhD Eng. IT exp. **Bogdan V. CIORUȚA**[3-5,*], MA stud. **Gabriela-Ionela HEREȘ**[6], Assoc. Prof. PhD Eng. habil. **Mirela-Ana COMAN**[7,8], Eng. IT exp. **Alexandru L. POP**[3,5]

[1] Technical University of Cluj-Napoca - North University Centre of Baia Mare, Faculty of Letters - Department of Specialty with Psychopedagogical Profile, Construction and Curricular Innovation (MA prog.), 76 Victoriei Str., 430083, Baia Mare, Romania

[2] "Little Prince" Extended Program Kindergarten, 8B Cuza Vodă Str., 430034, Baia Mare, Romania

[3] Technical University of Cluj-Napoca - North University Centre of Baia Mare, Office of Informatics, 62A Victor Babeș Str., 430083, Baia Mare, Romania

[4] Technical University of Cluj-Napoca - North University Centre of Baia Mare, Department of Mathematics and Computer Science, 76 Victoriei Str., 430072, Baia Mare, Romania

[5] Technical University of Cluj-Napoca - North University Centre of Baia Mare, Faculty of Letters - Department of Specialty with Psychopedagogical Profile, 76 Victoriei Str., 430083, Baia Mare, Romania

[6] Technical University of Cluj-Napoca - North University Centre of Baia Mare, Department of Mathematics and Computer Science, Computer Science and Software Engineering (MA prog). 76 Victoriei Str., 430072, Baia Mare, Romania

[7] Technical University of Cluj-Napoca - North University Centre of Baia Mare, Faculty of Engineering - Department of Mineral Resources, Materials and Environmental Engineering, 62A Victor Babeș Str., 430083, Baia Mare, Romania

[8] University of Agricultural Sciences and Veterinary Medicine from Cluj-Napoca, 3-5 Calea Mănăștur, 4000372, Cluj-Napoca, Romania

* bogdan.cioruta@staff.utcluj.ro

Abstract: *Effective ecological management of protected areas requires complex skills and data-driven decision-making. In this context, this article analyzes the pedagogical valences of Computer-Assisted Instruction (CAI) in the training and development of specialists in the field. CAI, through tools such as dynamic simulations, GIS (Geographic Information Systems) and Big Data analysis platforms, transforms the learning process from a theoretical and passive one to an interactive, practical and problem-solving one. The results of the literature review indicate that CAI significantly improves critical thinking, modeling and simulation skills, data management and interdisciplinary collaboration capacity, essential skills for adapting to the complex and dynamic challenges of nature conservation.*

Keywords: *Ecological management, protected areas, digital pedagogy, instructional-educational process*

1. Introduction

Protected areas - whether national parks, nature reserves or Natura 2000 sites - are fundamental elements of national and international biodiversity conservation strategies [1, 2]. They function, in the current conditions dictated by the information consumer society [3-5], as veritable natural laboratories and gene banks, playing a crucial role in maintaining regional and global ecological balance, but also in the sustainable development of local communities.

The efficient ecological management of protected areas - governed by management plans - involves particularly complex tasks, among which we can mention: continuous monitoring of the conservation status of species and habitats, the application of active conservation and protection measures, as well as the balanced management of the often conflicting interactions between natural factors (e.g., *climate change*, *biological invasions*, etc) and socio-economic ones (e.g., *tourism*, *local development*, *resource use*, etc) [6-8]. The success of this approach depends, to a large extent, on the quality of the professional training of the personnel closely involved.

In this sense, Computer-Assisted Instruction (CAI) is defined by the use of digital technologies - from interactive educational software and multimedia applications, to complex simulations, GIS (Geographic Information Systems) and e-learning platforms - as an essential tool in the teaching-learning-evaluation process, but especially as a crucial tool in the adequate professional training of future specialists with concerns regarding the appropriate ecological management of protected areas. Thus, we can state that in the current context of the ecological management of protected areas, CAL acquires crucial relevance, being a methodological response to operational challenges:

- the complexity of ecosystems in light of the fact that ecological phenomena (e.g., *population dynamics*, *the impact of climate change, biogeochemical cycles*, etc) are dynamic and abstract systems, difficult to observe and understand in and through the traditional didactic environment. CAI allows the visualization and manipulation of these processes through simulations.
- the volume of data (Big Data) requires the appropriate management of protected areas, knowing that the management of the latter generates large volumes of geospatial, species/habitat monitoring and socio-economic data, requiring in turn a set of advanced skills for analysis, processing and interpretation of information.
- the need for rapid and informed decisions arises in the context in which managers must make effective decisions under time pressure. CAI, through modeling and simulation tools, allows virtual testing of scenarios and the impact of different management measures before their implementation in the field, thus minimizing ecological and economic risks.

Thus, CAI is no longer perceived as just an auxiliary tool, but as a catalyst for a new educational paradigm - one that trains adaptable professionals with solid critical thinking and advanced technical expertise. The objective of this article is, in relation to the conditions presented above, to analyze the specific pedagogical valences of CAI and how they contribute to the development of essential skills necessary for both ecological and efficient, but also sustainable management of protected areas.

2. Literature review and associated research methodology

The literature review aimed to identify the specific contribution of Computer-Assisted Instruction (CAI) to the development of competencies in the field of applied ecology, as well as protected area management according to the Sustainable Development Goals (SDGs) [9-10]. The present research focused on articles that analyze the pedagogical effectiveness of digital tools in environmental contexts. Major academic databases were explored, including Web of Science®, Scopus®, Google Scholar®, ResearchGate®, but also specific e-learning and environmental education platforms (e.g., *nature conservation journals*, *dedicated ecological education blogs,* etc).
Within these, the searches were structured on three main intersecting axes: pedagogical axis (e.g., *e-learning*, *educational simulations*, *gamification*, etc), domain axis (e.g., *protected area management*, *ecological management*, *nature conservation*, etc) and tool axis (e.g., *GIS in education*, *ecological modeling*, *Big Data for the environment*, etc).
Particular priority was given to articles published in the last 10-15 years (2010-2025) to reflect recent developments in digital technologies. In this regard, a first search identified over 50 articles that fell into one or more of the three axes. Most dealt with either the general benefits of CAI or the technical applications (e.g., *GIS*, *modeling in PA management*, etc), without explicitly analyzing the pedagogical valences and the development of the competencies of specialists in the targeted reference field. From the perspective of relevant articles, only 8-12 articles directly or implicitly addressed the critical intersection between CAI and the development of specific competencies necessary for the adequate management of protected areas (e.g., *systems thinking*, *impact modeling capacity*, *multi-criteria analysis*, etc).
In light of the above, we can highlight that the existing literature highlights a gap between the technical use of digital tools (e.g., *GIS and simulations in ecological research*, etc) [11, 12] and their effective integration as pedagogical tools in professional training. Studies show that CAI-based simulations are superior to traditional methods in teaching ecological and abstract concepts (by relating to carrying capacity, positive/negative feedback from ecosystems), transforming theoretical knowledge into applied understanding.

Furthermore, relevant articles in the field of nature conservation demonstrate that the use of virtual scenarios (via CAI) improves the ability of students (future specialists) to make informed decisions and to critically and appropriately evaluate the impact of different management strategies in relation to protected areas. Equally, it has been confirmed that early exposure to GIS/RS (remote sensing) systems through CAI provides students with the necessary skills to effectively manage and visualize massive geospatial data, a skill now considered fundamental for a protected area manager. Consequently, this review justifies the need to detail, in the following sections, the specific way in which and through which CAI tools create distinct pedagogical valences, in Adaptive Ecological Management of Protected Areas (AEMPA), which can be systematically integrated into the curriculum associated with ecological management.

3. Results and Discussions in relation to the Implications of CAI in AEMPA

The conceptual analysis confirmed that Computer-Assisted Instruction (CAI) offers a set of distinct pedagogical valences that directly address the competence gaps identified in traditional ecological management of protected areas. These valences transform the learning process from one focused on memorizing knowledge to one focused on applied problem solving, by:

- ***Development of advanced technical and analytical skills*** - the most obvious contribution of CAI is at the level of technical skills needed to manage massive and dynamic data from protected areas, via:
  - ***modeling and systems thinking through dynamic simulations*** - the ecological simulations offered by CAI allow students to manipulate key variables (e.g., *hunting rate*, *drought impact*, *patrol budget allocation*) and observe the long-term consequences of these decisions on the ecosystem.
  - ***development of systems thinking*** - managers learn that point interventions can have unexpected domino effects (side effects) in other components of the system. This skill is vital to avoid ad-hoc decisions and to develop robust management plans, based on a holistic understanding.
- ***Active and problem-based learning*** - CAI facilitates the transition from a passive teaching model to a constructivist model, where the student (future specialist) builds his/her own knowledge through exploration and experiment, often relating to:
  - ***immediate application of knowledge*** - virtual case studies and serious games incorporate real ecological data and scenarios, which puts students in the role of managers who must resolve crises (e.g., *an epidemic*, *increased poaching*) using limited resources.
  - ***improved self-regulation of learning*** - the immediate feedback provided by CAI systems (simulation results) encourages students to review their decisions and understand the causes of failures, accelerating the learning curve and developing decision-making resilience.
- ***Interdisciplinary collaboration and communication skills*** - modern ecological management requires collaboration between ecologists, engineers, lawyers, sociologists and local communities, which can be achieved through:
  - ***collaborative platforms and tools embedded in analysis software*** - which allow simultaneous work on the same project (e.g., *the same GIS map or the same simulation model).*
  - ***training in teamwork and effective communication skills*** - students learn to justify their data-based decisions, in front of colleagues with different specializations, and to communicate complex results in an accessible format, essential skills for participatory management and negotiations with stakeholders in the protected area.

Although the benefits are clear, implementing CAI requires overcoming some obstacles. These include the high costs of software licenses (for GIS/advanced simulations), the need for a robust IT infrastructure and, most importantly, the methodological preparation of teachers to effectively integrate these tools into their pedagogy.

- ***Awareness of the ethical and financial impact of decisions*** - CAI introduces a realistic dimension, often omitted in theoretical study: budgetary, ethical and human resource constraints.
    - ***integration of socio-economic data*** - advanced simulations are not limited to ecology, but integrate cost-effectiveness modules and models for analyzing social conflicts (e.g., *the impact of access restrictions on local communities*).
    - ***development of decision-making responsibility and the capacity for ecological cost-benefit analysis*** - through CAI, students experience the fact that optimal measures from an ecological point of view may be economically unsustainable or socially unacceptable. This aspect forces them to find compromise solutions (trade-offs), negotiated and balanced, essential in the practical management of protected areas. CAI thus helps to form and strengthen an adequate ethical profile, because management mistakes can be simulated and discussed without having real consequences, giving due weight to future decisions.
- ***Improving adaptability and resilience*** - the environment in which protected area managers operate is most often characterized by a significant degree of uncertainty (e.g., *climate change*, *political developments*, *the emergence of new invasive species*, etc). CAI provides the necessary tools to develop flexible thinking, by directly reporting on:
    - ***stress testing scenarios*** - through CAI, extreme or worst-case scenarios can be quickly run (e.g., *a prolonged severe drought*, *a sudden increase in tourist pressure*) to see how the current management plan holds up.
    - ***increasing decision-making resilience and adaptive management*** - future managers learn not to rely on a single fixed plan, but to develop contingent strategies (plan B, plan C). CAI facilitates understanding of the concept of adaptive management - a continuous cycle of planning, implementation, monitoring and adjustment - by iteratively simulating these cycles.

This capacity for rapid adjustment is vital for the long-term survival of protected ecosystems. Consequently, CAI not only delivers technical knowledge, but also develops essential meta-cognitive skills (e.g., *ethical thinking*, *financial responsibility*, *adaptive flexibility*, etc). However, widespread adoption is conditional on investments in digital infrastructure and a curricular reform that places simulation and data analysis at the heart of training.

- ***Facilitating inter- and transdisciplinary integration of knowledge*** - ecological management is inherently transdisciplinary, requiring the integration of information from ecology, sociology, economics, law, geography, etc. CAI acts in this sense as a unifying framework for these fields, aiming at:
    - ***modular integration*** - modern CAI platforms (e.g., *advanced LMSs*) allow students to access and interconnect resources from distinct modules, from environmental legislation (text documents) to statistical models (analysis software) and field data (GIS files).
    - ***developing the capacity for information synthesis and interconnection*** - students no longer perceive disciplines as isolated entities, but as elements of a single management system. For example, an CAI exercise may require students to use legal knowledge (studied in a text module) to justify a zoning decision (applied in a GIS module), correlating it with cost-effectiveness analysis (from an economic simulation module). This prepares managers for the complexities of real life.
- ***The role of CAI in continuous and personalized/adaptive assessment*** - CAI offers significant advantages in the field of pedagogical assessment compared to traditional methods (classical written exams), which often fail to measure applicative skills.
    - ***a performance-based assessment*** - CAI-associated systems can record not only the final result of a simulation or a GIS analysis, but also the student's decision-making process (e.g., *the time spent on a specific task*, *the sequence of operations performed within a dedicated software application*, *the logic applied in modeling a population*, etc).
    - ***a continuous diagnostic and formative assessment*** - teachers can obtain a detailed picture of the strengths and gaps of each student, allowing for the

personalization, respectively the adaptation of the educational path. Thus, a student who excels in ecological modeling, but has difficulties in applying the legislation associated with the field, can receive a set of specific additional tasks. In the long term, this type of computer-assisted performance assessment ensures that graduates and professionals alike possess the necessary practical skills before being placed in critical protected area management positions.

The seven pedagogical valences outlined demonstrate that CAI transcends the role of a simple teaching tool. CAI acts as a simulative learning environment, essential for training protected area managers capable of navigating ecological complexity, making responsible decisions, adapting quickly to change, and integrating knowledge from diverse fields.

4. Perspectives and Proposals in relation to the Implications of CAI in AEMPA

For Computer-Assisted Instruction (CAI) to reach its full pedagogical potential in the field of ecological management of protected areas (see Fig. 1), a strategic approach involving investment, curricular innovation and inter-institutional collaboration is required.

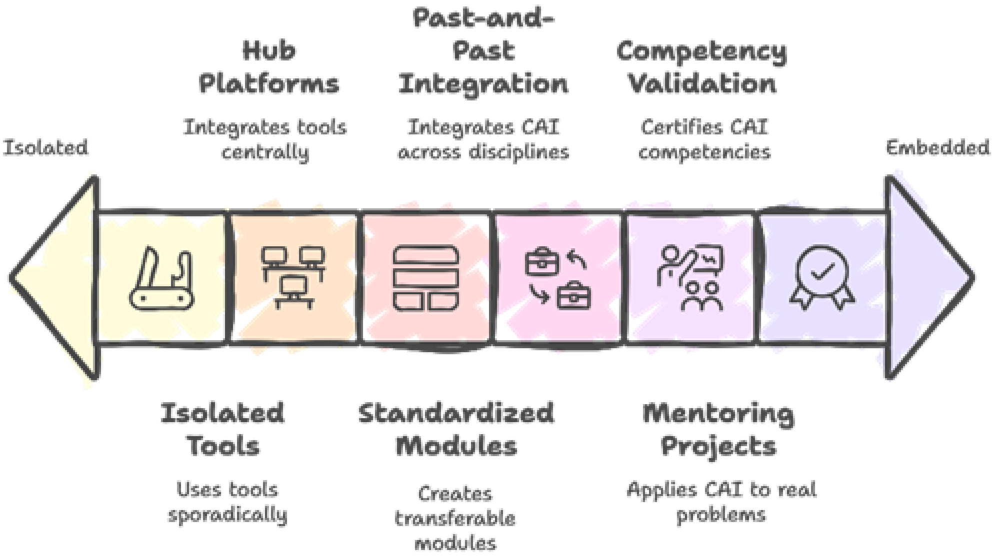

Fig. 1. An Infographic related to Perspectives and Proposals in relation to the Implications of CAI in AEMPA

The perspectives and proposals aim to transform the learning environment and align it with the professional requirements of the 21st century by:

- ***Developing integrated digital learning ecosystems*** by moving from the sporadic use of isolated tools (e.g., *a GIS software*, *a simple simulation*) to the creation of a Digital Learning Ecosystem (DLE) that is integrated and scalable, can be achieved through:
  - ***Hub platforms (integrated LMS)*** - creating a central platform (LMS) that not only hosts course materials, but also ensures native integration with specialized software (e.g., *GIS*, *R/Python statistical packages*, *Big Data analysis tools*, etc) through APIs (Application Programming Interfaces).
  - ***protected areas digital twins*** - development of dynamic virtual replicas of real protected areas, based on current monitoring data. These twins can be used for complex real-time adaptive management exercises.
- ***Standardization and democratization of resources (Open Education)*** by reducing the cost and accessibility barriers associated with high-performance commercial software, by:
  - ***promotion of OER and FOSS*** - supporting the development and use of Open Educational Resources (OER) and Free and Open Source Software (FOSS) - in particular QGIS for spatial analysis and ecological modeling packages based on open-source languages.

  - ***creation of standardized CAI modules*** - development of standardized and transferable CAI modules (e.g., *a module for simulating the ecological impact of road infrastructure*, etc), which can be quickly adopted by multiple educational institutions, ensuring a common competence base at the national level.
- ***Curricular reform and teacher training*** by shifting the emphasis from teaching about CAI to teaching through CAI via:
  - ***past-and-past integration*** - CAI competencies should not be taught in a single isolated course, but should be integrated transversally into all ecological management disciplines (from population ecology to environmental legislation and socio-economics).
  - ***methodological improvement programs*** - implementation of intensive in-service training programs (training the trainers) for teachers, focused on digital pedagogy and the effective use of simulations and analytical tools in the formative assessment process.
- ***Strategic academia-administration partnerships*** by ensuring that CAI training is directly relevant to the labor market and to the operational needs of protected area management.
  - ***computer-assisted mentoring projects*** - establishing partnerships between universities and PA administrations, where students, under the guidance of mentors, use CAI tools (e.g., *GIS*, *data analysis*, etc) to work on real problems in the management plan of protected areas.
  - ***competency validation*** - developing a framework for certifying digital competencies in ecological management, where success in complex simulations (CAI) is a condition for graduation or professional certification, guaranteeing that new specialists are job-ready.

These insights and proposals highlight the need for a deliberate transition to technology-based environmental education, essential to prepare a generation of ecological managers capable of successfully managing protected areas in the face of the growing challenges of the Anthropocene.

- ***Integrating emerging technologies*** by exploiting cutting-edge technologies to bring the natural environment directly into the classroom and to streamline the decision-making analysis process (see Fig. 2), through:
  - ***Virtual Reality (VR) and Augmented Reality (AR) for immersion*** - developing VR/AR applications that allow students to take virtual field trips to hard-to-reach or dangerous protected areas (e.g., *coral reef monitoring*, *cave monitoring*, etc). This improves spatial awareness and provides ecological context without the logistical costs and environmental impact.
  - ***AI and Machine Learning (ML) in Decision Support*** - integrating AI and ML-based CAI modules to process Big Data sets (e.g., *satellite images*, *acoustic recordings*, etc) and to provide predictive management recommendations (e.g., *prediction of poaching trajectory*, *areas with maximum risk of biological invasion*).

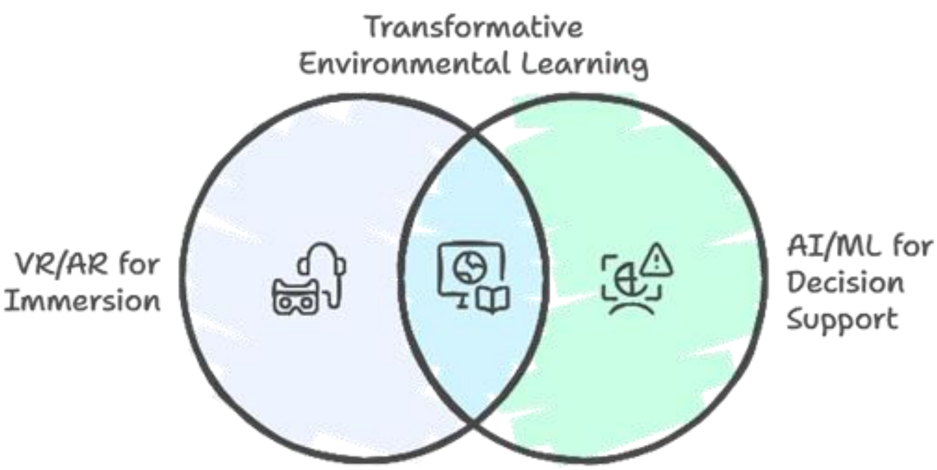

Fig. 2. An Infographic related to synergy of VR/AR and AI/ML in AEMPA

- ***Establishing a framework for digital certification of skills*** by creating a formal system for recognizing digital skills acquired through CAI, to increase the professional credibility of graduates requires, among others:
    - ***specific micro-certifications*** - developing micro-certifications or digital badgings (e.g., *GIS analysis certificate in conservation*, *population dynamics modeling certificate*, etc) that are recognized by employers (especially by protected area administrations and environmental NGOs).
    - ***partnerships with the software industry*** - collaborating with software developers (e.g., *ESRI for GIS and/or other developers of ecological simulations*, etc) to offer common certifications, which certify that the training is aligned with industry technical standards.
- ***Intensifying pedagogical research focused on CAI*** - requires the need to shift the emphasis from implementing CAI to the scientific evaluation of its pedagogical effectiveness in ecological management, which can be achieved through:
    - ***controlled impact studies*** - conducting quasi-experimental studies that compare the performance of groups of students trained through CAI with that of groups trained through traditional methods, measuring not only knowledge retention, but also the quality of management decisions made in simulated practical scenarios.
    - ***methods for assessing systemic thinking*** - developing new assessment tools (specific metrics) that can objectively measure the development of systemic thinking, decisional resilience and ethical judgment - skills that are best outlined through interaction with CAI simulations, but which are difficult to quantify through classical methods.

5. Conclusions and recommendations

Computer-Assisted Training (CAI) is no longer an auxiliary option, but an indispensable and strategic component in modern professional training for the ecological management of protected areas. The present research has demonstrated that CAI generates a set of 7 essential pedagogical valences that go beyond the simple transmission of information, contributing to the development of a complete manager profile, capable of managing the complexity and dynamism of ecosystems, through:

- ***transformation of skills*** - CAI moves the center of gravity from theoretical knowledge to applied skills, especially in the field of systems thinking and geospatial analysis (GIS/Remote Sensing), fundamental skills for the development and adjustment of management plans of protected areas.
- ***responsible decisions*** - by using dynamic simulations, CAI develops the capacity of managers to make responsible, ethical and ecologically cost-benefit-based decisions, experiencing the long-term consequences of interventions without affecting the environment.
- ***adaptability and synergy*** - CAI facilitates active learning and develops decision-making resilience to uncertainty (Adaptive Management), while acting as an effective framework for integrating inter- and transdisciplinary knowledge (ecology, economics, sociology, etc), essential in participatory management.

In conclusion, the future of nature conservation depends on our ability to train a generation of ecological managers equipped with the necessary analytical tools and decision-making ethics, and, in this specific context, the CAI is the essential vehicle for achieving this vision.

References

[1] McCarthy, C., J. Banfill, and B. Hoshino. "National parks, protected areas and biodiversity conservation in North Korea: opportunities for international collaboration." *Journal of Asia-Pacific Biodiversity* 14, no. 3 (2021): 290-298. DOI10.1016/j.japb.2021.05.006.

[2] Alberts, R.C., F.P. Retief, A.J. Bond, C. Roos, and D.P. Cilliers. "What Future for Protected Areas? Analysing the Mismatch between South Africa's Pre-existing Protected areas System and the Declared vision in Contemporary Conservation Policy." *Environmental Management* 74, no. 6 (2024): 1274-1286. DOI10.1007/s00267-024-02051-8.

[3] He, X.Y., and H.B. Wei. "Biodiversity conservation and ecological value of protected areas: a review of current situation and future prospects.” *Frontiers in Ecology and Evolution* 11 (2023): 1261265. DOI10.3389/fevo.2023.1261265.
[4] Adams, V.M., A.L.M. Chauvenet, N. Stoudmann, G.G. Gurney, D. Brockington, and C.D. Kuempel. "Multiple-use protected areas are critical to equitable and effective conservation.” *One Earth* 6, no. 9 (2023): 1173-1189. DOI10.1016/j.oneear.2023.08.011.
[5] Múnera-Roldán, C., M.J. Colloff, J. Pittock, and L. van Kerkhoff. "Aligning adaptation and sustainability agendas: lessons from protected areas.” *Mitigation and Adpatation Strategies for Global Change* 29 (2024): 64. DOI10.1007/s11027-024-10159-9.
[6] Coman, M. *Ecological management* / *Management ecologic*. Cluj-Napoca, Editura Risoprint, 2009.
[7] Coman, M. *Ecosystem investigation techniques* / *Tehnici de investigare a ecosistemelor*. Cluj-Napoca, Editura Risoprint, 2011.
[8] Coman, M., and A. Dăscălescu. *Guide to good environmental practices* / *Ghid de bune practici de mediu*. Cluj-Napoca, Editura Risoprint, 2008.
[9] Chen, Y.H. "Development of the Animal Conservation Digital Learning Aids and Assessments through the Industry-University Collaborative Course.” *Sustainability* 13, no. 14 (2021): 7524. DOI10.3390/su13147524.
[10] Arishi, H., N. Falkner, C. Treude, and T. Attapattu. "Understanding the Computer Science Student Experience Through the Lens of System Ecology.” Paper presented at the 2024 IEEE Frontiers in Education Conference (FIE), Washington, DC, USA, October 13-16, 2024.
[11] Wang, C.C., C.L. Lo, M.C. Hsu, C.Y. Tsai, and C.M. Tsai. "Implementation a Context-Aware Plant Ecology Mobile Learning System.” *Sage Open* 10, no. 2 (2020): 2158244020920701. DOI10.1177/2158244020920701.
[12] Zhang, J., Z.Z. Chen, C. Duan, and X.L. He. "Reshaping the Teaching Ecology with the Construction of Informationalized Teaching Mode.” Paper presented at the 4th International Conference on Distance Education and Learning ICDEL '19, Shanghai, China, May 24-27, 2019.