Original Article
IRSTI 14.35.09 10.51889/2960-1649.2025.65.4.008

MANAPOVA SALTANAT, AFANASENKOVA IRINA, SHAIKHOVA BAKHYT, DAUTOVA ZUKHRA, TANTYBAYEVA BATIMA*

Sarsen Amanzholov University of East Kazakhstan, Ust-Kamenogorsk, Kazakhstan

*Address of correspondence: Irina Afanasenkova, Department of Chemistry, Sarsen Amanzholov East Kazakhstan University, 30th Guards Division St. 34, Ust-Kamenogorsk, 070002, Republic of Kazakhstan, https://orcid.org/0000-0002-5369-825X, E-mail: iafanasenkova@vku.edu.kz /Tel.: +7 777 578 5787

Pedagogical feasibility of the Systemic-Structural Approach in Ecological-Chemical Education

Abstract

Introduction. The study explores the concept of pedagogical expediency as a system-forming criterion of sustainable didactics, addressing the need for a new educational paradigm in the context of global ecological and cognitive challenges. Traditional linear didactics is shown to lose semantic relevance under conditions of ecological crisis, cognitive overload, and transformation of human subjectivity. *Methodology.* Within the framework of Systemic-Structural Didactics (SSD), a multi-level model of pedagogical expediency was developed, encompassing biophysiological, psychological, social, and ecosystemic levels. The study applies structural modeling, content analysis, and interdisciplinary synthesis to design diagnostic and developmental tools for ecological-chemical education (ECE). *Results.* The research formalizes the SSD architecture, which includes ontological, functional, and operational contours, ensuring systemic alignment of educational values, content, and methods. The proposed matrix of correspondence between levels of expediency supports the design of sustainable learning processes. The model of ecological metacompetence (EMC) is presented as an integrative educational outcome that unites cognitive, ethical, behavioral, and adaptive dimensions. *Scientific novelty.* The study introduces and substantiates the concept of ecological metacompetence and integrates it into the SSD framework as a key indicator of sustainable and ethically grounded learning. The transition from a utilitarian to an ontological logic of pedagogical activity is theoretically justified. *Practical significance.* The proposed SSD-based model can be applied in the design and evaluation of interdisciplinary courses, particularly in ecological and chemical education, ensuring coherence between knowledge acquisition, ethical reasoning, and sustainable behavior.

Keywords: pedagogical expediency, systemic-structural didactics, ecological-chemical education, ecological metacompetence, ontology of education, didactic architecture, three-contour model.

Introduction. Global processes of ecological instability, technogenic pressure, and sociocultural uncertainty impose new demands on education. These demands suggest that knowledge reproduction is no longer sufficient. In this regard, there is a need for the formation of meaningful, sustainable behavioral strategies and critical reflection. It is therefore important to note that modern educational systems, predominantly based on linear, technological, and standardized didactics, often fail to adapt to these challenges (Sterling, 2001; UNESCO, 2017). These issues become particularly salient in ecological-chemical education (ECE), an interdisciplinary field that combines chemistry as the science of matter transformation with ecology as the science of interconnections, sustainability, and biospheric thresholds.

Chemistry is undoubtedly one of the most powerful instruments for transforming nature, while ecology may be interpreted as the moral and systemic corrector of these transformations. However, in educational practice, this synergy is often lost. For instance, chemistry is typically taught as a technical or natural science, and ecology as a set of abstract concepts.

It can be observed that an emerging contradiction exists between the potentially transformative and humanizing capacity of ecological-chemical education and its actual reduction to a set of factual knowledge, devoid of ontological and ethical density. In pedagogical theory, this contradiction reveals a deeper deficit, which can be interpreted as the absence, at the core of didactic models, of the notion of pedagogical expediency, understood not merely as external efficiency, but as the coherence of goals, means, meanings, and consequences of education. In the philosophy of education, the idea of expediency has deep historical roots. Aristotle, in Nicomachean Ethics, already asserted that an action can be considered virtuous only when it is meaningful and directed toward the good (Brown, 2009). Later, Kant (1785) associated rational activity with the notion of "purposive rationality" (Zweckrationalität) as a practical correlation of means and ends based on the moral law (Kant, 1785). In the 20th century, this tradition was further developed by Jürgen Habermas, who contrasted purposive rationality with communicative rationality, emphasizing the necessity of social legitimacy and ethical justification of educational actions (Habermas, 1981). However, 20th–21st century didactics was dominated by instrumentalism, an orientation toward measurability, standardization, and competencies without a transcendental aim. Even in the competence-based paradigm (OECD, 2005), the axiological dimension is often marginalized. As a result, there is no structural place for the question: why are we teaching this, why in this particular way, and what are the consequences of this education for the future of the world?

Researchers argue that the key to addressing this problem lies in the formalization and implementation of a multi-level structure of pedagogical expediency as the foundational criterion of didactic architecture (Abdimanapov et al. 2024; Manapova et al. 2025). In order to embed expediency as a systemic principle into a didactic model, a corresponding paradigm is required. If such a paradigm does not exist, it must be created. This analysis relies on the proposed concept of Systemic Structural Didactics (SSD), a theoretical and applied model that includes three interrelated levels: the ontological contour, which encompasses goals, meanings, and worldview foundations; the functional contour, which addresses content modules and interdisciplinary links; and the operational contour, which focuses on forms, tools, tasks, and assessment. Each of these levels must be verified in terms of its pedagogical expediency (Sanat, 2022). Unlike traditional didactics, where methods are selected "for the goal" without deep axiological assessment, SSD implies a holistic validation of educational action against the values of sustainability, responsibility, and meaningfulness.

The purpose of our study is to theoretically justify and practically construct pedagogical expediency as the core of systemic-structural didactics within ecological-chemical education. This includes the development and visualization of a multi-level model of pedagogical expediency, the construction of a three-contour didactic architecture of ECE, a comparison of traditional and SSD didactics according to the criterion of expediency, the introduction and structuring of ecological metacompetence as the resultant vector of education, and the proposal of diagnostic and visual tools suitable for implementation in school and university teaching. In our research, we propose a structural and multi-level model of pedagogical expediency, a formalism of three-contour didactics combining philosophy, methodology, and design, the concept of ecological metacompetence as a set of reflexive, practical, and value-based modalities, and an integrative framework for reconstructing chemistry-ecology curricula through the lens of sustainable thinking and semantic reflection.

As previously mentioned, the philosophical concept of expediency stands out sharply in the works of Aristotle, Immanuel Kant, and Jürgen Habermas, where the emphasis is placed on the alignment between goals, means, and the meaning of action. In classical pedagogy, Sanat (2022) considers expediency as an integral category that encompasses physiological, psychological, cognitive, and value-based levels. In traditional approaches, expediency is often reduced to operational efficiency, lacking semantic density and meta-orientation.

It can be observed that modern didactic studies increasingly demonstrate a transition toward multi-layered models of education. These works typically emphasize the importance of reflection and meaning, yet the formalization of the level of expediency remains absent. The three-contour model of didactics proposed in this study resonates with the ideas of spiral learning (Raisch, 2018) and von Bertalanffy's (1957) system thinking, offering a multi-level approach to designing both lessons and the educational environment. UNESCO emphasizes that Education for Sustainable Development (ESD) must cultivate values and responsibility, not merely knowledge and skills. Nevertheless, in practice, especially within chemical education, this often results in isolated ecological modules. Sterling (2001) highlights the gap between the declared goals of ESD and the current paradigm of education, which remains technocratic and narrowly instrumental.

Green Chemistry, or sustainable chemistry, is recognized as a key direction. Its 12 principles (Anastas & Warner, 1998) and subsequent research outline the necessity of integrating environmental consciousness directly into science curricula. Studies by Parchmann et al. (2006) and Burmeister et al. (2012) provide successful cases of chemistry teaching through the lens of sustainability. Contemporary research calls for the integration of systems thinking into chemistry education. For example, Orgill (2019) emphasizes the need to develop students' ability to perceive systemic connections between chemical reactions and sustainability. Proposals involving concept maps and expert opinion elicitation have proven effective in fostering systemic perception. Thus, based on the review, there was compelling justification for proposing a model that integrates a multi-level structure of pedagogical expediency, embeds it into the didactics of ecological-chemical education, facilitates the formation of ecological metacompetence, and overcomes the limitations of the traditional approach.

Materials and Methods. In the methodology of this study, the researchers proceeded from an understanding of didactics as a form of sociocultural organization of knowledge, meaning, and action. Within the notation of post-nonclassical pedagogy (Benin, 2015), education is not limited to the transmission of content; it rather functions as a reflexive and value-organized system. Such an interpretation requires a shift from a functional logic of instruction to a semantic logic of expediency, in which every pedagogical action must be understood in the context of its consequences, values, and systemic effects. The foundations of this approach lie in classical systems philosophy, axiological pedagogy (Cichosz, 2021), and structural-organizational approaches to educational practice. Here, the research proceeded from the principle of methodological monadism, that is, the correspondence of each methodological unit to a holistic framework of action. This principle allowed us to form a three-contour framework for analysis and design. An important role was also played by the ontological turn in pedagogy (Snaza et al., 2014), which insists on interpreting education as an act of world-formation, rather than merely the transmission of knowledge about the world. We argue that expediency, in this context, is not about pragmatism, but rather a mode of ontological alignment of pedagogical actions with the context of sustainability, life, and being.

As the conceptual core of our study, we adopted the Systemic-Structural Didactics (SSD) model, which synthesizes ideas from activity theory, axiological, and systemic approaches. SSD, as mentioned earlier, presupposes the existence of three interrelated contours: the ontological (goal setting, meanings, values), the functional (content structure, modules, connections), and the operational (technologies, tasks, visual and assessment tools). It is necessary to embed within each of these contours the criterion of pedagogical expediency, which differs by level, from biological feasibility to ecological systemicity. Also essential is the inclusion of a resultant category, ecological metacompetence, as an integral indicator of didactic effectiveness. The present study is qualitative-structural in nature and combines philosophical-normative analysis, modeling, and applied didactic comparative studies as the main methods.

Table 1

Research Methods and Their Functional Justification

Method	Justification and Function
Philosophical-ontological analysis	To identify the hierarchy of value foundations in pedagogical action
Structural modeling	To construct the multi-contour architecture of expediency and SSD-didactics
Comparative analysis	To compare traditional and SSD-didactics in terms of pedagogical validity
Axiological verification	To test the models for alignment with the values of sustainability and semantic richness
Conceptual visualization	To represent the model in the form of schemes suitable for integration into pedagogical practice

The researchers also employed methods of philosophical hermeneutics (Supena, 2022), axiological scaling, and morphological analysis. The present study postulated the following null hypothesis: *pedagogical expediency can be formalized as a multi-level structure embedded within SSD-didactics*. Verification of this hypothesis was interpreted through the construction and formalization of a five-level model of pedagogical expediency, visual representation of the three-contour didactic architecture, comparative analysis with traditional didactics based on criteria of coherence, meta-orientation, and value density, and conceptual validation of the model via philosophical foundations (Aristotle 1984; Habermas, 1981; Kant, 1785) and contemporary didactic theories. Overall, this study's methodological approach is based on structural modeling, which involves the decomposition of pedagogical expediency into levels, the identification of links between levels and didactic actions, the construction of a three-contour model as an architectural framework, and the introduction of a resultant category in the form of ecological metacompetence (Table 1).

Results. Levels of Pedagogical Expediency: Historically, the concept of pedagogical expediency has remained at the periphery of didactics, yielding priority to operationalized notions such as "efficiency, "learning outcomes," and "competence." However, the contemporary crisis in education, amid climatic, bioethical, and cognitive challenges, demands a deeper framework. This research argues that this framework lies in the value-semantic verification of every pedagogical action. Thus, the present study posits that pedagogical expediency should not be interpreted as a one-dimensional criterion, but as a hierarchically organized system of modalities, ranging from biophysical feasibility to systemic ecological mission.

This model is constructed based on:

1) Axiological decomposition as the identification of value modalities governing pedagogical action;

2) Systemic logic in the notation of von Bertalanffy (1957), where each level of expediency serves and is subsumed by a hierarchically superior one;

3) Aristotle's teleological philosophy, where action is considered virtuous when directed toward and performed for the sake of the good;

4) Hans Jonas's ethics of responsibility (1979, as cited in Jonas, 1985), where the imperative ("ought") applies not only to the individual but also to the future world.

Accordingly, this study conceptualized the model of pedagogical expediency through five levels, each functioning as a condition and regulator of pedagogical action, and to visualize their structure, the researchers present the Summary Table 2.

Table 2
Summary Table of Expediency Levels and Categorical Correspondences

Level	Focus	Type of Regulation	Meaning Category	Task Class in ECE
BE	Safety, workload	Physiological	Functional	Accounting for reagents, conditions, and ventilation
PE	Motivation, interest	Psycho-cognitive	Psycho-methodological	Use of visual models, case studies
DE	Method, goal, result	Didactic	Logical-methodological	Designing modular blocks
EE	Value, responsibility	Ethical	Axiological	Bioethics topics, chemistry, and morality
EsE	Contribution to sustainability	Systemic	Ontological	Designing tasks based on SDG themes

Overall, this study's model is hierarchical. Each subsequent level includes and governs the previous ones, similar to multilevel regulation in biology. This is not a mere linear scale, but a modally systemic pyramid, where upper levels set the normative boundaries for lower ones. In ecological-chemical education, our model of pedagogical expediency enables the design of lessons with internally consistent architecture, the diagnosis of "deficient" program fragments (toxic experiments without ethical reflection), integration of sustainability themes on a systemic rather than episodic level, and the formation of ecological metacompetence as an integrative outcome across all levels. Thus, our model systematizes pedagogical expediency for the first time as a multi-layered category. It introduces an ontological level of regulation of pedagogical action, creates a foundation for a new verification pedagogy, where expediency, not efficiency, becomes the meta-criterion, and adapts systemic logic to the context of sustainable education and humanitarian chemistry.

The Three-Contour Model of SSD: The three-contour model of Systemic-Structural Didactics (SSD) developed by us is based on the integration and interpretation of:

1) The systems approach, in which each level functions as a subsystem performing a specific function within the overall didactic architecture;

2) The philosophy of levels of reality (Langacker, 2023), according to which pedagogical activity possesses ontological, functional, and operational layers;

3) The functional morphology of didactics (Vegas, 2021), where each element of the learning process corresponds to an appropriate level of content and meaning;

4) The concept of semantic density of education, in which the quality of didactics is determined by the coherence of levels.

Structurally, our SSD model consists of three contours:

I. Ontological Contour (OC)

Purpose: Forms the goal-based foundation, the value framework, and the worldview axis of educational action.

Content elements: Goals, paradigms, justifications, and future scenarios.

Examples in ECE: "Why do we study chemistry?" "How does chemistry affect the biosphere?" "What is our responsibility as chemists?"

Connection to expediency: Correlates with Ethical (EE) and Ecosystemic Expediency (EsE).

II. Functional Contour (FC)

Purpose: Defines the structure and logic for the implementation of content, forming modules, connections, and progressions.

Content elements: Interdisciplinary links, modularity, and conceptual nodes.

Examples in ECE: Thematic chains such as "atom-molecule-reaction consequence," integration of ecology, biochemistry, and geochemistry in case studies, and construction of progressions like "experiment-explanation-predictive model."

Connection to expediency: Corresponds to Didactic (DE) and Psychological Expediency (PE).

III. Operational Contour (OpC)

Purpose: Specifies the forms, methods, and tools for content implementation.

Content elements: Methodologies, tasks, visualizations, and assessment.

Examples in ECE: Micro-experiments with safe reagents, assignments on ecological footprints of substances, and visualization of reaction chains through diagrams.

Connection to expediency: Linked with Biological (BE), Psychological (PE), and partially with Didactic Expediency (DE). We can highlight several key features of the SSD model that directly emerge from its three-contour structure.

Thus, our model functions as a multi-level architecture for designing, implementing, and evaluating education. It is not limited to the function of instruction but includes projective, ethical, and transformational dimensions. Let us illustrate the SSD architecture dynamically, from design to concrete action, through a stepwise scheme.

1) Stage 1: The teacher constructs the course/lesson beginning from the ontological level, defining value orientations and worldview frameworks.

2) Stage 2: These orientations are formalized into functional modules with didactic logic (progressions, links, task types).

3) Stage 3: Operational implementations are selected: forms, visualizations, methods.

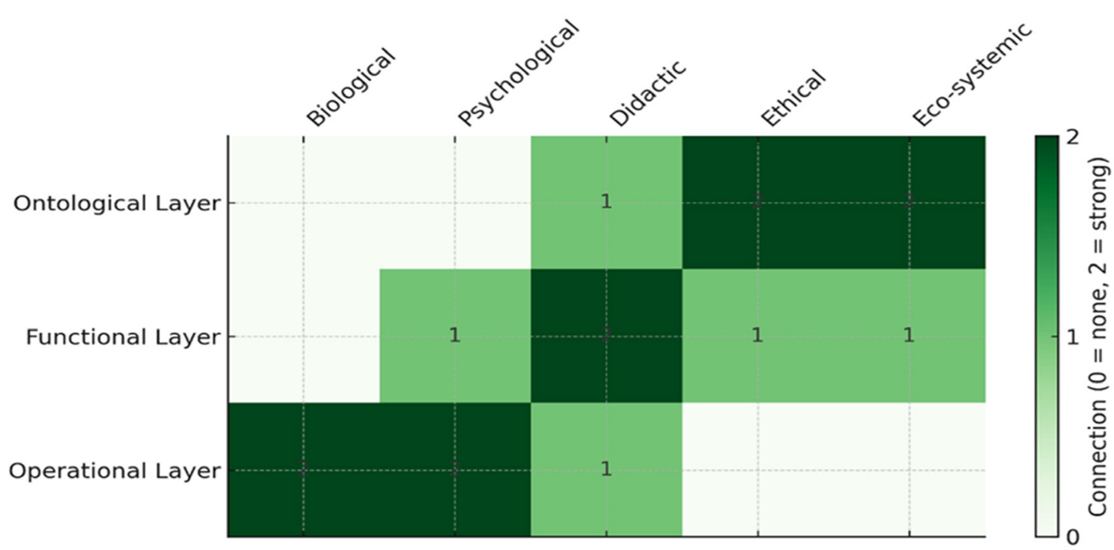
At all stages of this architectural scheme, the model of levels of pedagogical expediency is applied as a diagnostic tool: Does the chosen action correspond to the value vector?

This example demonstrates that our model enables formal verification of didactics using axiological criteria, integrates the value level into didactic design, adapts to schools, colleges, universities, and online environments, and can serve as a foundation for didactic audits, methodical development, and innovative educational programs. Indeed, in traditional didactics, a chemistry lesson is typically structured as: Goal- Content Method Assessment.

In the present research's SSD model, this sequence is replaced with the architecture: Value-Worldview Framework (OC), Modular Content Structure (FC), Operational Implementation (OpC). Each pedagogical action is verified through the model of pedagogical expediency levels.

Figure 1

Matrix of Correspondence Between SSD Layers and Levels of Pedagogical Expediency [Insert visualization here – Matrix grid with saturation zones: 2 = dark green (high), 1 = light green (moderate), 0 = absent]



In the matrix of Figure 1, green zones with high saturation (value 2) visually indicate areas of main semantic and didactic load. Light zones (value 1) indicate secondary or indirect interactions. For instance, the functional contour influences ethical expediency, albeit not directly. From the matrix, we can infer that the Ontological Layer has the strongest association with both Ethical (2) and Ecosystemic (2) expediency. This confirms that value foundations of pedagogical decisions are formed primarily within the ontological contour. The Functional Layer occupies a bridge position, being connected to four levels, especially to Didactic (2) and Psychological (1). The Operational Layer is primarily linked to Biological (2) and Psychological (2), that is, with immediate impact on the body and perception of the learner. Thus, coherent lesson design requires engaging at all levels, from physiological safety to systemic responsibility. Overall, the matrix we propose can be used as a tool for auditing and self-assessment in lesson, module, or course design. Specifically, each pedagogical action can be checked for its inclusion in the contours and correspondence to the levels of expediency.

As for the model as a whole, it is particularly well-suited for the development of didactic maps and checklists, analysis of curricula by the principle of structural density, and visualization of the educational ecosystem. Moreover, integrating the three-contour model into ECE lessons transforms chemistry education from a "science of formulas" into a pedagogy of sustainable thinking, ensures structural expediency of every didactic element, introduces a reflective ecological framework previously absent in formal chemistry, and offers a scalable model for schools, colleges, universities, and online learning. Traditional and Systemic-Structural Didactics in Terms of Pedagogical Expediency: Throughout the 20th and 21st centuries, the dominant model in science education, including chemistry, has been technological didactics, which follows a linear logic: goal-content-method assessment. It must be acknowledged that this scheme proved relatively effective under conditions of standardized and mass instruction. However, in today's world, characterized by increasing complexity, transdisciplinarity, and a crisis of values, this model appears to be losing didactic validity. In contrast, our Systemic-Structural Didactics (SSD) is built on an architectural, nonlinear, and multi-level principle: ontological framing functional modules operational forms. Each step in this structure is assessed against a multi-level scale of pedagogical expediency. This distinction can be illustrated through the following comparative tables 3 and 4.

Table 3
Traditional vs. SSD Didactics

Criterion	Traditional Didactics	SSD Didactics
Educational Goal	Knowledge transmission and assessment	Formation of meaning and systemic responsibility
Lesson Structure	Linear, fragmented	Modular, contour-hierarchical
Expediency	Single-level, operational	Five levels, from physiology to ecosystem
Outcome Assessment	Reproductive testing	Diagnostics of competences and meta-outcomes
Work with Values	Episodic, optional	Central component of the ontological contour
Visualization and Digital Tools	Auxiliary function	Structuring and design instrument
Role of the Student	Passive recipient	Meaning-making agent
Sustainable Development (SDG)	Thematic inclusion	Integrated into lesson logic and structure

We can now compare both models across each level of pedagogical expediency (Section 4.1).

Table 4
Comparison of Models by Level of Expediency

Level of Expediency	Traditional Model	SSD Didactics
Biological (BE)	Often violated (stress, overload)	Principle of gentle and mindful instruction
Psychological (PE)	Partially ensured via motivation	Active use of psycho-design principles
Didactic (DE)	Predominantly frontal method	Methodical flexibility and alignment
Ethical (EE)	Almost absent	Core system-forming component
Ecosystemic (EsE)	Thematically introduced	Embedded into the didactic structure

Overall, we identify eight key parameters by which Systemic-Structural Didactics (SSD) fundamentally differs from traditional models.

1. The goal of education shifts from information transmission to the formation of meaning and responsibility, aligning with the paradigm of education as transformation of consciousness, not just knowledge instrumentation.

2. The lesson structure evolves from linear to modular, allowing flexible integration of interdisciplinary connections, progressions, and contexts.

3. Expediency becomes an internal structural category, formalized through a five-level model, from biological feasibility to ecological systemicity.

4. Assessment transforms from a control mechanism into a verification tool for meta-effects, including ecological metacompetence.

5. Work with values in SSD is embedded into the ontological contour, while in traditional didactics, it is optional or absent.

6. Visualization assumes a central role, not as decoration, but as a semantic scaffold and didactic interface.

7. The student is no longer a passive recipient but a subject of design, interpretation, and action.

8. Integration of sustainable development (ESD) in traditional models is possible only thematically, while in SSD it is structurally systemic.

Indeed, some researchers argue (Burmeister, 2012) that the implementation of Sustainable Development Goals (SDGs) is impossible if traditional didactics remains the sole model. Only systemic educational architectures capable of accounting for value, ethical, and systemic dimensions can cultivate the necessary level of student competence.

SSD didactics does not dismiss the achievements of traditional approaches. Rather, it incorporates them into a broader action architecture, where efficiency is combined with ethical responsibility, and knowledge with sustainability.

In general, transitioning to the SSD model requires:

1) Redesigning curricula and modules;

2) Retraining teachers with an emphasis on the philosophy and structure of pedagogical action;

3) Developing diagnostic tools based on levels of pedagogical expediency;

4) Implementing digital visual interfaces that support architectural instructional design.

Ecological metacompetence: It is not difficult to observe that, under the conditions of climate, resource, and ethical instability, the world is entering an era of transformation. In this context, educational systems are expected not only to train professionals but also to form subjects capable of thinking in terms of sustainability and interconnection, acting upon ecological values, and adapting to rapidly changing environmental and technological conditions.

The competency-based approach, adopted in educational systems since the 2000s, has proven insufficient, as it focuses primarily on operational capabilities (knowing, doing, applying), while neglecting the ontological and ethical foundations of action. We argue that within the framework of Systemic-Structural Didactics (SSD), integrated with a five-level model of pedagogical expediency, a transition is possible from standard competencies to ecological metacompetence (EMC) as the integrative outcome of ecological-chemical education (ECE).

We define ecological metacompetence (EMC) as the learner's sustained ability to recognize and reflect on the consequences of chemical and technological decisions in the biosocial context; to act based on values of sustainability, ethical responsibility, and systemic interdependence; and to adapt behavioral and professional practices in conditions of ecological uncertainty.

Based on this definition, the structure of EMC can be interpreted as follows (Table 5):

Table 5

Structure of Ecological Metacompetence

Component	Description	Link to SSD and Expediency
Awareness	Knowledge of ecological problems and chemical consequences	Operational contour (BE, PE)
Understanding	Comprehension of interconnections and systemic effects	Functional contour (DE)
Responsibility	Ethical evaluation of actions and recognition of consequences	Ontological contour (EE)
Eco-behavior	Application of sustainable solutions and choice of alternatives	All contours, predominantly OpC
Adaptation	Ability to transform behavior in response to changing environments	Meta-component integrating all levels

It should be emphasized that the EMC model is not autonomous. Rather, it emerges as a result of integrating all three contours and all five levels of pedagogical expediency. This makes it a valid indicator of didactic maturity and the sustainability of education. Moreover, we can assert that in the era of automation and employment crisis, ecological metacompetence may become a new form of post-economic subjectivity, shaping not only profession but also ways of thinking, acting, and assuming responsibility. Specifically, EMC can be integrated into national education standards as a multidisciplinary outcome, uniting natural sciences, philosophy, pedagogy, and digital literacy. It may also serve as a basis for international benchmarking of the quality of environmental education. Thus, we consider ecological metacompetence not as a by-product of ecological-chemical education, but as its primary didactic-humanistic outcome. It cannot be cultivated within linear didactics, but only through architectural and systemic approaches, such as multi-contour and multi-layered pedagogical models (SSD). In this context, EMC combines value-based, cognitive, and behavioral modalities, enabling the learner not only to know but to act responsibly (Table 6). To support practical implementation, we offer a model for assessing ecological metacompetence within an ECE course. This model is designed in both academic and practical formats and can be integrated into assessment systems at the level of lessons, courses, programs, and modules. Let us recall that ecological metacompetence is interpreted here as a multi-level integrative quality that encompasses cognitive, ethical, behavioral, and adaptive elements. It cannot be evaluated through traditional tests or standard assessments. Instead, it requires a mixed model, combining quantitative and qualitative indicators, formative and summative assessment, reflective, behavioral, and project-based tools, and validation through the levels of pedagogical expediency. We propose the following assessment framework for ecological metacompetence.

Table 6

EMC Assessment Components

Component	Assessment Indicator	Assessment Method
Awareness	Recognition of environmental issues and chemical consequences	Survey, oral questioning

Understanding	Comprehension of systemic relations and consequences	Concept maps, systems-based essays
Responsibility	Ethical reasoning on chemistry and ecology issues	Ethical case analysis
Eco-behavior	Selection of sustainable solutions in practical contexts	Scenario-based tasks, project assignments
Adaptation	Flexibility, reflection, and behavior adjustment	Reflective essays, feedback mechanisms

Each component may be evaluated on a 4-point scale.

Level	Criterion
0	Absence of the component
1	Fragmented or partial understanding
2	Holistic but unstable application
3	Stable behavior/reflection/action

Accordingly, the total EMC score is the sum of points across five components (range: 0–15). Additionally, competence profiles can be generated, displaying individual scores for each component, e.g., using radar charts. Group profiles can also be constructed, as well as before/after course comparisons and week-by-week progress tracking. General methodological recommendations for implementation are as follows.

1) Integrate EMC assessment throughout the module, not only at the end, with reflection after each phase;

2) Use mixed methods, including observation and self-assessment;

3) Engage learners in co-developing assessment criteria to enhance metacognitive awareness;

4) Visualize progress. This helps learners recognize and value their own development.

The EMC model is based on the five-level structure of pedagogical expediency, validated through the three-contour SSD framework, aligned with global SDG frameworks and ethical pedagogy, and has strong instrumental potential for implementation in schools, colleges, universities, and digital learning platforms.

Discussion. The model of expediency adopted in our study is not functional-instrumental but ontological. It is grounded in a philosophical reconstruction of the concept of telos as both meaning and purpose embedded in being itself. This radically distinguishes our approach from utilitarian interpretations of education as mere "preparation for the market" or "training in applicable skills" (Biesta, 2010). Thus, any form of instruction that does not incorporate the category of the good cannot be considered pedagogical in the strict sense. This brings our concept close to the tradition of ontological pedagogy (Klafki, 1998) and modern post-normal pedagogy of sustainability (Sterling, 2001), in which education is conceived as a transformation of the subject, not merely the transmission of content. It is important to emphasize that the SSD model, as demonstrated in our study, is not simply another taxonomy or skills matrix. Its novelty lies in multi-level, nonlinear, and topological thinking about the educational process. Here, the operational contour corresponds to tactical actions, the functional contour to strategic construction of relations and contexts, and the ontological contour to existential foundations - values and worldview.

This aligns SSD with synergetic didactics (Haken, 2006), where learning is not a linear progression but a self-organizing cognitive attractor, integrating knowledge into the structure of the subject. In this sense, we shift didactics from a discipline of methods to a discipline of architectures and transitions, and the role of the teacher becomes that of an architect of the semantic educational field. Modern critiques of the competency-based approach (Hyland,

2007) point out its reduction of the subject to a carrier of functions. In contrast, we propose moving beyond this horizon by introducing the concept of ecological metacompetence (EMC) - the ability of a subject not merely to act, but to think in categories of sustainability and interdependence, to make decisions under ethical and ecological uncertainty, and to reflectively adapt to the evolving landscape of planetary challenges. Unlike so-called "green competencies," this research's EMC model is founded on ontological grounds (SSR-contours), has a clear structure with cognitive-ethical components, and proposes a didactic design and assessment model embedded into the architecture of the course. In this way, in our interpretation, EMC becomes not an auxiliary result but a new pedagogical paradigm. Specifically, the SSD model demands the abandonment of the linear logic of the lesson, where one goal corresponds to one method and one form of assessment. Instead, we propose a matrix architecture, where the contours (operational, functional, ontological), levels of expediency (from basic to eschatological), and components of EMC are interconnected, forming a topological educational field, by analogy with fields in physics or systems biology.

The present study proposes that such a conditional field is subject to design (through didactic pathways), navigation (through learning tracks), and evaluation (through competence profiles and meta-indices). The model has certain limitations, such as a limited empirical base, the need for adaptation across educational levels, and possible challenges in subject-oriented systems, yet it offers prospects for integration into SDG 4.7 metrics, application within UNESCO ESD2030 and the Earth Charter initiatives, and incorporation into digital platforms as a flexible competence-semantic track, demonstrating its transversality (Santesmases, 2020). The model can be adapted not only to ECE but also to biology (via the concept of a "biocenosis of thinking"), social studies (through systemic analysis of decisions), and mathematics (through topology and models of sustainability).

The findings of the present study confirm the hypothesis that pedagogical expediency is a transcendental criterion of the scientific nature of educational action. It is the inclusion of expediency, at all levels, from task formulation to result evaluation, from content to course architecture, and from instruction to ontological assembly of the subject, that ensures a transition from pedagogy as function to pedagogy as transformation of thought and being (Freire, 1970). Thus, Systemic-Structural Didactics, implemented through the lens of pedagogical expediency, not only responds to the challenges of sustainability but also reassembles the very nature of education, restoring its status as ethically conscious, ontologically embedded, and transformatively directed action. Let us once again emphasize expediency as the criterion of true education and express this position in the form of a maxim: "Education without ontology is merely operation; ontology without education is merely silence."

Classical 20th-century didactics, grounded in technocratic models, relied predominantly on instrumentalist epistemology, treating knowledge as an object to be transmitted, measured, and acquired. However, the challenges of the 21st century, climatic, civilizational, and cognitive, require not more knowledge, but a transformation of the very form of thinking (Silva, 2009). Accomplishes precisely this: a transition from knowledge as information to knowledge as an ontological stance. It restores the lost ontological vector of education, in which learning is not only about mastering the external but also about assembling the internal. In essence, the model we propose raises a radical question. Is everything we teach pedagogically justifiable? Pedagogical expediency becomes a filter for epistemic validity. That is, knowledge that does not lead to understanding, action, responsibility, and adaptation is not genuine knowledge in the pedagogical sense. This leads to an epistemological shift, from an emphasis on verifiable truth (in the logical-positivist model) to transformative truth, aligned with the horizon of the subject, their environment, and values. Hence, education in our model should be viewed as a process of epistemogenesis, not only assimilation of knowledge but the generation of new forms of epistemological relations to the world: from singularity to multiplicity of perspectives, from transmission to constructive generation, and from object to meaning and ontological dimension. This directly aligns the SSD approach with the paradigms of radical constructivism (Jarvinen, 1998), cognitive epistemology (Luhmann, 2017), and meta-education (Jayadi, 2022), where the learner does not merely receive the world but constructs it. Ultimately, the most significant philosophical threshold emerges in connection with ecological metacompetence. Here, knowledge ceases to be neutral and becomes ethically charged (every knowledge entails consequences), ecologically embedded (knowledge alters the biosphere), and ontologically responsible (knowledge shapes the image of reality).

Thus, ecological-chemical education cannot be a mere transmitter of concepts and formulas. It must become a platform for the redefinition of the human-nature relationship. And this demands a new epistemology of education - one that is responsible, holistic, and expedient. What began as a local investigation into didactics in ecological-chemical education has ultimately brought us to the limits of pedagogical rationality itself. Our SSD model may be interpreted not only as a tool for course design but as a mode of thinking - an epistemological threshold demanding redefinition of what we consider knowledge, what we recognize as outcomes, and what we call education. In this sense, pedagogical expediency becomes a new criterion of truth, and truth itself is no longer static but cultivated and revealed within the structure of the subject.

Conclusion. Thus, our study has convincingly demonstrated that pedagogical purposiveness should be interpreted not as an auxiliary category but as a foundational principle for educational design. This approach enables us to distinguish formal instruction from genuinely pedagogical action by relating each didactic practice to its value-based, adaptive, and meta-level context. Conceptually, the proposed model of system-structural didactics (SSD) constitutes an architecture of three interrelated contours (operational, functional, and ontological), and this architecture is authentically validated through a five-level structure of purposiveness, ranging from biological foundations to ecosystemic responsibility. We believe that this structure not only ensures the logical and semantic coherence of educational actions but also generates new trajectories of pedagogical thinking. Overall, the concept of ecological metacompetence (EMC) developed in this study captures the integral outcome of ecological-chemical education by linking cognitive, ethical, and adaptive components. In our view, it can serve as an indicator of pedagogical maturity and be applied both in student assessment and in course design, particularly within the frameworks of sustainable education and global SDG targets. Accordingly, we may confidently affirm that our SSD and EMC models possess transversality, are applicable across disciplines, are scalable to digital environments, and can serve as a foundation for a new generation of educational programs oriented toward value-laden meaningfulness and structural adaptability.

References

Abdimanapov, B., Kumarbekuly, S., & Gaisin, I. (2024). Technology for Achieving Learning Objectives Through a System-Activity Approach and the Development of Critical Thinking in Geography Studies. *Journal of Ecohumanism, 3*(8), 11989-12003. https://doi.org/10.62754/joe.v3i8.5797

Anastas, P. T., & Warner, J. C. (2000). *Green chemistry: theory and practice*. Oxford University Press. https://academic.oup.com/book/53104

Aristotle. (1984). Nicomachean Ethics, Book II, Chapter 4, 1105a b. Translated by W.D. Ross. In: The Complete Works of Aristotle, ed. J. Barnes. Princeton University Press, 1984.

Benin, V. L. (2015). Pedagogy in the Era of the Post-Non-Classical Science. *The Education and Science Journal*, (6), 122. https://doi.org/10.17853/1994-5639-2012-6-122-135

Biesta, G. (2010). A new logic of emancipation: The methodology of Jacques Rancière. *Educational theory*, *60*(1), 39-59. https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1741-5446.2009.00345.x

Brown, L. (Ed.). (2009). *The Nicomachean Ethics*. Oxford University Press. https://books.google.com/books?hl=en&lr=&id=TUX7uoQyPUMC&oi=fnd&pg=PR5&dq=Aristotle.+Nicomachean+Ethics,+Book+II,+Chapter+4,+1105a%E2%80%93b.+Translated+by+W.D.+Ross.+In:+The+Complete+Works+of+Aristotle,+ed.+J.+Barnes.+Princeton+University+Press,+1984.&ots=mOJNcKQz7R&sig=2iWH9nH9KqqIjHDiOV4AaIPi7sg

Burmeister, M., Rauch, F., & Eilks, I. (2012). Education for Sustainable Development (ESD) and chemistry education. *Chemistry Education Research and Practice*, *13*(2), 59-68. https://pubs.rsc.org/en/content/articlehtml/2012/rp/c1rp90060a

Cichosz, M. (2021). Axiological Foundations of Social Pedagogy: Search Areas. *Roczniki Pedagogiczne*, *13*(4), 35-43. https://www.ceeol.com/search/article-detail?id=1019440

Freire, P. (1970). Pedagogy of the Oppressed. The Continuum International Publishing Group. *Inc.: New York, NY*.

Habermas, J. (1981). Theorie des kommunikativen Handelns, Frankfurt a. *M.: Suhrkamp*.

Haken, H. (2006). Synergetics of brain function. *International journal of psychophysiology*, *60*(2), 110-124. https://www.sciencedirect.com/science/article/pii/S0167876006000067

Hyland, K., & Tse, P. (2007). Is there an "academic vocabulary"?. *TESOL Quarterly*, *41*(2), 235-253. https://onlinelibrary.wiley.com/doi/abs/10.1002/j.1545-7249.2007.tb00058.x

Jarvinen, E. M. (1998). The Lego/Logo Learning Environment in Technology Education: An Experiment in a Finnish Context. *Journal of Technology Education*, *9*(2), 47-59. https://eric.ed.gov/?id=EJ563616

Jayadi, K., Abduh, A., & Basri, M. (2022). A meta-analysis of the multicultural education paradigm in Indonesia. *Heliyon*, *8*(1). https://www.cell.com/heliyon/fulltext/S2405-8440(22)00116-5

Jonas, H. (1984). *The imperative of responsibility: In search of an ethics for the technological age*. University of Chicago Press. https://www.amazon.com/Imperative-Responsibility-Search-Ethics-Technological/dp/0226405974

Kant, I. (1785). *Grundlegung zur Metaphysik der Sitten*. Riga: Johann Friedrich Hartknoch

Klafki, W. (1998). Characteristics of critical-constructive Didaktik. *Didaktik and/or curriculum: An international dialogue*, 307-330.

Langacker, R. W. (2023). Levels of Reality. Lublin Studies in Modern Languages and Literature, 47(1), 11–36. https://doi.org/10.17951/LSMLL.2023.47.1.11-36

Luhmann, N. (2017). Evolution of science. *Epistemology & Philosophy of Science*, *52*(2), 215-233. https://www.pdcnet.org/eps/content/eps_2017_0052_0002_0215_0233

Manapova, S., Shaikhova, B., Kumarbekuly, S., Mikushina, I., & Afanasenkova, I. (2025). A set of online tools for teaching chemistry, considering a systematic approach to the educational process. *International Journal of Innovative Research and Scientific Studies*, *8*(1), 1363-1379. https://elibrary.ru/item.asp?id=82154838

OECD (2005). *The Definition and Selection of Key Competencies. Executive Summary*. Paris: OECD

Orgill, M., York, S., & MacKellar, J. (2019). Introduction to systems thinking for the chemistry education community. *Journal of Chemical Education*, *96*(12), 2720-2729. https://pubs.acs.org/doi/abs/10.1021/acs.jchemed.9b00169

Parchmann, I., Gräsel, C., Baer, A., Nentwig, P., Demuth, R., & Ralle, B. (2006). "Chemie im Kontext": A symbiotic implementation of a context-based teaching and learning approach. *International journal of science education*, *28*(9), 1041-1062. https://www.tandfonline.com/doi/abs/10.1080/09500690600702512

Raisch, S., Hargrave, T. J., & Van De Ven, A. H. (2018). The learning spiral: A process perspective on paradox. *Journal of Management Studies*, *55*(8), 1507-1526. https://onlinelibrary.wiley.com/doi/abs/10.1111/joms.12397

Sanat, K., Nurbol, U., Bakhadurkhan, A., Anargul, S., Zukhra, D., & Gulfat, K. (2022). World Journal on Educational Technology: Current Issues. https://www.ceeol.com/search/article-detail?id=1074260

Santesmases, JS (2021). Study of the transversality of content in Physical Education through competency-based curricula. *Challenges: new trends in physical education, sport, and recreation*, (40), 419-429. https://dialnet.unirioja.es/descarga/articulo/7706238.pdf

Silva, S. R. D. (2001). Review: Edgar Morin: The seven necessary knowledges for the education of the future. *ETD-Educação Temática Digital* , *2*(3), 138-142. https://www.ssoar.info/ssoar/bitstream/handle/document/10554/ssoar-etd-2001-3-rez-silva.pdf?sequence=1

Snaza, N., Sonu, D., Truman, S. E., & Zaliwska, Z. (2016). *[Introduction to] Pedagogical Matters: New Materialisms and Curriculum Studies*. Peter Lang Publishing, Inc.. https://scholarship.richmond.edu/bookshelf/219/

Sterling, S., & Orr, D. (2001). *Sustainable education: Re-visioning learning and change* (Vol. 6). Totnes: Green Books for the Schumacher Society. https://www.researchgate.net/profile/Stephen-Sterling-2/publication/289505456_Sustainable_education/links/609bf59e458515a04c59a648/Sustainable-education.pdf

Supena, I. (2022). Gadamer's Philosophical Hermeneutics on Religious Language and COVID-19. *Filosofija. Sociologija*, *33*(3), 310-317. https://www.ceeol.com/search/article-detail?id=1064875

UNESCO (2017). Education for Sustainable Development Goals: Learning Objectives. Paris: UNESCO Publishing.

Vegas, R. A. M. (2022). Knowledge of morphology, morphological awareness, and lexical learning." Diffused" objectives in Secondary Education. *Tejuelo*. https://www.academia.edu/download/94817387/4106_Texto_del_articulo_15656_2_10_20211209.pdf

Von Bertalanffy, L. (1957). Quantitative laws in metabolism and growth. *The quarterly review of biology*, *32*(3), 217-231. https://www.journals.uchicago.edu/doi/abs/10.1086/401873

Information about authors:

Manapova Saltanat, Doctoral of Pedagogical Sciences of Sarsen Amanzholov East Kazakhstan University, Department of Chemistry, 070002, Republic of Kazakhstan, Ust-Kamenogorsk, 30th Guards Division st.34, ORCID ID: 0000-0002-2641-8347, email: smanapova@vku.edu.kz,

Bakhyt Shaikhova, Candidate of Pedagogical Sciences, Associate Professor of Sarsen Amanzholov East Kazakhstan University, Department of Chemistry, 070002, Republic of Kazakhstan, Ust-Kamenogorsk, 30th Guards Division st.34, ORCID ID: 0000-0001-8567-6752, email: bshaihova@vkgu.kz

Afanasenkova Irina, Candidate of Pedagogical Sciences, Associate Professor of Sarsen Amanzholov East Kazakhstan University, Department of Chemistry, 070002, Republic of Kazakhstan, Ust-Kamenogorsk, 30th Guards Division st. 34, ORCID ID: 0000-0002-5369-825X, email: iafanasenkova@vku.edu.kz

Dautova Zukhra, Candidate of Pedagogical Sciences, Associate Professor of Sarsen Amanzholov East Kazakhstan University, Department of Chemistry, 070002, Republic of Kazakhstan, Ust-Kamenogorsk, 30th Guards Division st.34, ORCID ID: 0000-0003-2017-7009, email: zdautova@vku.edu.kz

Tantybayeva, Batima, Candidate of Pedagogical Sciences, Associate Professor of Sarsen Amanzholov East Kazakhstan University, Department of Chemistry, 070002, Republic of Kazakhstan, Ust-Kamenogorsk, 30th Guards Division st.34, ORCID ID: 0000-0001-5750-6481, email: bati_54@mail.ru

