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REPORT ON LITERATURE REVIEW ON COMPLEX SYSTEMS, SYSTEMS THINKING, AND SUSTAINABLE DEVELOPMENT:

THEORETICAL ISSUES THROUGH GREEN AND APPLIED CHEMISTRY

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ABSTRACT

In the current work, a systematic search of the international literature was carried out in order to identify publications that bring out the connections of complexity science and/or systems thinking with specific science disciplines, namely applied chemistry and green-sustainable chemistry. In addition, literature search was administered in order to identify publications which are related the theoretical framework governing systems thinking as well as methods for its assessment. Following their identification, the publications content was critically reviewed and analyzed in order to gain insights related to the aspects of complexity science and/or systems thinking that could be implemented in higher (tertiary) education in order to provide young students' (and future world leaders) with the skills and competences which are necessary for facing the emerging problems of increasing complexity in an uncertain world.

1. Introduction

The literature review was carried out via a systematic search of publications connected with the following three thematic areas: a) Applied Chemistry, b) Green and sustainable chemistry and c) Systems thinking-theoretical framework and assessment. Each publication was read through and subsequently critically reviewed with regard to its relevance with complexity science and/or systems thinking. In addition, the possible strong points of each publication regarding practical implications (for example in the teaching praxis) as well as the advancement of thinking related to the systems approach were identified. Content analysis was carried out in order to provide insights that could be useful for the development of a toolbox aiming at fostering systems thinking approaches in tertiary education. The results subsequently presented are the outcome of reviewing in total 100 publications of which 33 were related with Applied Chemistry, 32 with Green and Sustainable Chemistry and 35 with the theoretical framework and assessment of systems thinking.

2. Results Achieved

2.1 Complexity Science

Complex systems are considered as non- linear systems described by three observed behaviors:

- Behaviors that are directly associated with individual components, which are simply observed in parallel within a large system.
- Behaviors that can be predicted through detailed understanding of the properties of individual components.
- Behaviors that cannot be predicted, no matter how thorough our understanding of individual components is.

The last two behaviors are emergent system-level phenomena and therefore they can be observed only in the complex system. [1]

The complex systems cannot be predicted directly from initial conditions and thus emergent phenomena are considered as a key feature of complex systems.[2] Consequently, complexity is defined based on the interactions among elements of a system, on the extent to which systems may self-organize, and on the emergence of properties of the whole system that are not exhibited by the individual elements.[1]

A key feature of complex systems is the fact that there are often nonlinear relationships between causal variables and system-level behaviors or properties. The concept of nonlinearity is rooted in chaos theory and suggests that a small agitation of the system can be amplified nonlinearly to create a substantial effect elsewhere in the system. Complex systems have emergent properties that can only be ascribed to the system as a whole and not to any individual component of the system. These unique properties result from interactions between organized parts of the system. Complex systems and their properties are dynamic. [3] An understanding of complex systems relates to understanding and recognition of concepts and principles about a particular domain represented by key (often dynamic) phenomena and their inter-relationships. For example, every chemical reaction is part of a larger system, which will have inherent complexity related to function, structure, and state.

A structured approach to thinking about complex issues that stimulates new and deeper insights is defined as systems thinking. [4] Specifically, the art of systems thinking involves the ability to represent and assess dynamic complexity (e.g., behavior that arises from the interaction of a system's agents over time), both textually and graphically. Feedback processes and time delays are pervasive in complex systems and often have a significant effect on their dynamics. The different dimensions of complexity include the ability to recognize and interpret feedback relationships, the ability to recognize and analyze nonlinear relationships between cause and effect, and the ability to estimate and analyze the impact of time delays. [1, 4]

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Systems thinking is also presented as a way in developing students' complex systems reasoning. Adopting a mechanistic-reasoning approach in the modeling of complex systems is suggested as one of the core elements of chemical systems thinking. Thus, in chemistry educational contexts, systems thinking shows a commitment to (a) enhance students' knowledge, skills, and values in chemistry through a focus on the interconnections between different chemical phenomena; (b) improve students' knowledge of the influence of chemistry on planetary and societal issues; and (c) prepare students to make informed decisions and to address the complex global challenges of the 21st century. [5]

2.2 Sustainable development

Systems thinking is viewed as a critical and holistic approach that provides the necessary capacities for a critical consideration of all parts and their interactions to realize the goals of sustainable development and the three dimensions of sustainability: environmental, economic, and social. Students can establish connections to relevant United Nations Sustainable Development Goals (UN SDGs) by adopting a systems thinking approach for guiding decision making for more sustainable solutions.[6]

Systems thinking can significantly contribute to improving sustainability at a global level by considering each consequence that may arise from a research topic. Applying green chemistry principles and systems thinking concepts to safety instruction not only teaches students to assess risk for performing a reaction but also extends to sustainability considerations such as feedstocks and waste produced. The study of the life cycle of chemicals connects green metrics and system thinking tools to recognize environmental and societal impacts. Green and sustainable chemistry technologies can contribute to social equity and environmental justice. Integrating social and environmental justice frameworks into chemistry courses and/or programs requires a multi-faceted approach that involves many pieces of a complex puzzle.[7]

2.3 Inter-disciplinarity and trans-disciplinarity

Chemistry as a complex and mature discipline has increasingly been drawn into engagements across disciplines, the nature of which can take a number of different forms: (a) multidisciplinary — bringing together knowledge and problem-solving approaches from a host of fields that can each contribute, 'side by side', to different stages or aspects of problem-solving; (b) interdisciplinary — developing expertise in working across the boundaries between chemistry and other disciplines and transferring methods from one discipline to another; (c) transdisciplinary — beyond interdisciplinary (which still implies the autonomy of subjects working in cooperation), creating a new synthesis of chemistry and other subjects in which knowledge, methods and solutions are developed holistically: recognizing that valuable knowledge can be found in the spaces between defined disciplines, addressing the complexity of problems and the diversity of perceptions of them; and representing a transition from compartmentalized, corrective, problem-solving approaches to systemic approaches that seek to prevent the occurrence of problems. [8]

A systems thinking approach seeks to develop an understanding of interconnections among physical, biological, and environmental systems. In addition, according to this approach, the understanding of the interdisciplinary and connective nature of these systems is crucial to solving several global problems. Systems thinking prepares students for collaborative interdisciplinary work. Since it is well-accepted that interdisciplinary approaches to research are required to solve problems at both global and local levels, young chemists seeking to enter the workforce must possess experience working in interdisciplinary projects and acquire analytical and experimental skills necessary to solve emerging problems. [9]

2.4 Students´ understanding

The review of publications reveals several issues that contribute to the students´ understanding of chemistry and its linkages to other disciplines. First, an examination of facets of complexity in diverse contexts (e.g., within an individual reaction system; between systems and at different scales) can provide important gains in understanding. Second, systems thinking is considered as a critical interdisciplinary skill that describes the cognitive flexibility needed to work collaboratively on problems faced in modern societies, which continue to grow in complexity. Third, the construct of systems thinking has been emphasized as an understanding of the patterns that connect various systems ideas, methods, theories, or models focusing on the whole as well as the parts to form a more complete understanding of the system. Finally, systems thinking could be considered essential in order to engage learners in thinking about complex systems which will subsequently promote science literacy. Consequently, understanding complex systems is fundamental to developing an authentic understanding of science and understanding of science is needed to guide responsible action.

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2.5 Development of a toolbox

Key challenges for the global society such as poverty, hunger, climate change, and ocean acidification need to be approached in an interdisciplinary way. In this way, there is a need for a chemistry curriculum that goes beyond “pure chemical” content and incorporates interdisciplinary learning, reflects chemistry’s impact on society, the environment, and the economy. Interdisciplinary research projects employ critical thinking, problem solving, and creativity as part of the scientific method. Translating undergraduate research in nanotechnology, renewable energy, and sustainability into lesson plans and engaging in outreach to diverse populations promotes equity in science education and encourages underrepresented groups to seek careers in a scientific field. The use of chemistry experiments in combination with digital pre- and post-laboratory learning materials incorporating perspectives from biology, agriculture, economics, politics, and geography into chemistry education is proposed to overcome disciplinary boundaries. [10, 11]

2.6 Discussions with teachers

Discussions with teachers could be related with the development of interdisciplinary experiments allowing either multiple departments (such as chemistry and biology) to collaborate to facilitate the session, or students to benefit from gaining exposure to green chemistry and practical hands-on opportunities to employ some of the practices as well as through an interdisciplinary component that prompts them to recognize the interconnectedness and interdependence of chemistry with other disciplines (e.g. how chemistry and microbiology are interrelated). The development of systems thinking based laboratory activities dealing with issues that concern young people, could provide fruitful ideas. Some aspects of well-designed laboratory activities could involve the following: (a) investigate an environmental or health issue related to a consumer product, (b) reinforce and practice benchtop chemistry laboratory skills, (c) analyze and interpret data and (d) promote discussion of alternative sustainable consumer choices. [12]

2.7 Discussions with employers

A sustainable manufacturing approach will enable economic growth combining with environmental and social sustainability and will be realized via collaboration within a multidisciplinary community including chemists, biologists, engineers, environmental scientists, economists, experts in management, and policy makers. Systems thinking in the business case shows the impact of moving from a linear to a more circular economy approach, from the simple and mundane through to the complex or radical benefits for the triple bottom line: moving from showing progress, building confidence, and raising the company profile through to creating ambition, yielding rapid advances, and fostering long-term thinking. [13]

Products, feedstocks, and manufacturing processes need to integrate the principles of green chemistry and green engineering under an expanded definition of performance that includes sustainability considerations. This transformation will require the best of the traditions of science and innovation coupled with new emerging systems thinking and systems design that begins at the molecular level and results in a positive impact on the global scale. For instance, a cost-effective approach to toxicity reduction through system thinking could improve both the financial and environmental performance for industry and the community. [14]

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References

[1] Aubrecht, K.B., Dori, Y. J., Holme, T. A., Lavi, R., Matlin, S. A., Orgill, M., & Skaza-Acosta, H. (2019a). Graphical tools for conceptualizing systems thinking in chemistry education. *Journal of Chemical Education, 96*(12), 2888-2900.

[2] Blonder, R., & Rosenfeld, S. (2019). Integrating the human element in the responsible research and innovation framework into systems thinking approaches for teachers' professional development. *Journal of Chemical Education*, *96*(12), 2700-2703.

[3] York, S., & Orgill, M. (2020). ChEMIST Table: A Tool for Designing or Modifying Instruction for a Systems Thinking Approach in Chemistry Education. *Journal of Chemical Education*, *97*(8), 2114-2129.

[4] Vachliotis, T., Salta, K. and Tzougraki, C. (2014). Meaningful understanding and systems thinking in organic chemistry: Validating measurement and exploring relationships. Research in Science Education, 44(2), 239-266.

[5] Flynn, A.B., Orgill, M., Ho, F.M., York, S., Matlin, S.A., Constable, D.J., & Mahaffy, P.G. (2019). Future directions for systems thinking in chemistry education: Putting the pieces together. *Journal of Chemical Education*, *96*(12), 3000-3005.

[6] Ginzburg, A.L., Check, C.E., Hovekamp, D.P., Sillin, A.N., Brett, J., Eshelman, H., & Hutchison, J.E. (2019). Experiential learning to promote systems thinking in chemistry: evaluating and designing sustainable products in a polymer immersion lab. *Journal of Chemical Education, 96*(12), 2863-2871.

[7] Lasker, G.A., & Brush, E.J. (2019). Integrating social and environmental justice into the chemistry classroom: a chemist's toolbox. *Green Chemistry Letters and Reviews*, 12(2), 168-177.

[8] Matlin, S.A., Mehta, G., Hopf, H., & Krief, A. (2016). One-world chemistry and systems thinking. *Nature Chemistry*, *8*(5), 393-398.

[9] Nagarajan, S. & Overton, T. (2019). Promoting systems thinking using project-and problem-based learning. *Journal of Chemical Education*, *96*(12), 2901-2909.

[10] Blatti, J.L., Garcia, J., Cave, D., Monge, F., Cuccinello, A., Portillo, J., Juarez, B., Chan, E., & Schwebel, F. (2019). Systems thinking in science education and outreach toward a sustainable future. *Journal of Chemical Education*, 96(12), pp.2852-2862.

[11] Zowada, C., Siol, A., Gulacar, O., & Eilks, I. (2019). Phosphate recovery as a topic for practical and interdisciplinary chemistry learning. *Journal of Chemical Education, 96*(12), 2952-2958.

[12] Mahaffy, P.G., Matlin, S.A., Holme, T.A. and MacKellar, J. (2019). Systems thinking for education about the molecular basis of sustainability. *Nature Sustainability*, 2(5), 362-370.

[13] Summerton, L., Clark, J.H., Hurst, G.A., Ball, P.D., Rylott, E.L., Carslaw, N., Creasey, J., Murray, J., Whitford, J., Dobson, B., & Sneddon, H.F. (2019). Industry-Informed Workshops to Develop Graduate Skill Sets in the Circular Economy Using Systems Thinking. *Journal of Chemical Education, 96*(12), 2959-2967.

[14] Moore, S.B. and Ausley, L.W. (2004). Systems thinking and green chemistry in the textile industry: concepts, technologies and benefits. *Journal of Cleaner Production*, 12(6), 585-601

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