Systems Thinking: A New Perspective for Chemistry Educators

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Abstract - *In recent times, there has been a predominant focus on reductionism in both scientific research and education. Although this reductionist perspective has yielded substantial advancements in our understanding of the natural world and has led to remarkable technological progress, it falls short in addressing the complex global challenges we face today, such as sustainability, pollution, climate change, and poverty. To ensure continued progress in science as a whole, and specifically in the field of chemistry, and to empower individuals to participate effectively and democratically in science-related policy decisions, it is imperative to complement the commonly employed reductionist approaches in chemistry research and education with a more comprehensive and holistic framework. One such approach is systems thinking [1]. This article explores the historical evolution of systems thinking, elucidates its key characteristics, and highlights the essential skills and competencies associated with this perspective. Furthermore, it aims to equip chemistry educators with fundamental knowledge about systems thinking so that they can contemplate why and how to incorporate this approach into the education of aspiring chemists and future global citizens.*

Key Words: Systems Thinking, General Public, Philosophy, Problem Solving, Decision Making, Learning Theories

1. INTRODUCTION

Although the reductionist approach has significantly enhanced our understanding of the natural world and led to remarkable technological advancements, it falls short in tackling global challenges like sustainability, pollution, climate change, and poverty [2]. To supplement the reductionist approaches commonly employed in chemistry research and education, a more comprehensive perspective is required [3]. This study aims to familiarize the chemistry education community with systems thinking- an approach that examines and addresses complex behaviours and phenomena holistically. The study followed the subsequent steps-

(i). Identifying the consequences and limitations associated with reductionist approaches.
(ii). Exploring the historical development and characteristics of systems thinking approaches through discussion.

2. REDUCTIONIST PARADIGMS IN SCIENCE AND SCIENCE EDUCATION

According to Fang and Casadevall, reductionism in scientific research refers to the belief that complex systems or phenomena can be comprehended by analyzing their simpler components [4]. This reductionist perspective heavily influences our thinking, exemplified by the Newtonian worldview that views the world through a reductive lens. It assumes the possibility of objective knowledge and employs analysis as the means to attain such knowledge. Consequently, the reductionist perspective portrays the natural world as deterministic and predictable, explained by linear cause-and-effect relationships [1]. This reductionist outlook within science has also influenced science education. MacInnis elucidates that within a reductionist framework, the educational process aims to transmit the knowledge possessed by the teacher to the student. In this model, the teacher or curriculum specialist determines the content and sequence of the units to be taught [5].

3. PITFALLS AND CONSTRAINTS OF REDUCTIONISM

The application of reductionist approaches in science has proven highly fruitful in expanding our understanding of the natural world. By breaking down complex problems into simpler components, scientists have gained valuable insights and facilitated easier study and comprehension. These reductionist methods have also enabled advancements in measurement capabilities and the development of technologies that have become indispensable in our daily lives [6]. Nonetheless, it is important to acknowledge the inherent limitations of reductionist approaches [7]. As the adage goes, a whole is often greater than the sum of its parts, and scientists who solely focus on individual components may overlook crucial interrelationships or unique properties and behaviours arising from their interactions.

Reductionist approaches in science education, initially designed to boost student participation in science and technology fields after the Sputnik era, have yielded positive outcomes [2]. However, these approaches have associated limitations and challenges, primarily rooted in the reduction of knowledge to isolated, context-independent facts that can be memorized and assessed

[6]. One significant concern is that reductionist methods are inconsistent with how individuals truly learn [8]. Rather than learning disconnected facts out of context, research indicates that meaningful learning occurs when new information is connected to previously acquired knowledge and is taught within relevant contexts [8]. Additionally, reductionist education tends to compartmentalize facts within individual disciplines, hindering students' ability to generalize and apply knowledge in novel situations [5]. Finally, reductionist approaches often claim an objective view of scientific knowledge, neglecting the influence of human perspectives in scientific practices and data interpretation [5].

4. POTENTIAL OF SYSTEMS THINKING APPROACHES

'Systems thinking' entails examining and comprehending concepts from a comprehensive viewpoint, emphasizing interconnections and interdependencies. This paper does not advocate for the replacement of reductionist approaches with systems thinking approaches. Instead, it proposes that systems thinking should be utilized as a complement to reductionist approaches in both chemistry research and chemistry education.

In order to educate future global citizens effectively, the integration of systems thinking approaches is crucial. Given the increasingly global and interconnected nature of challenges such as sustainability, it is essential for chemists to be equipped with a systems thinking perspective. Chemists play a vital role in developing innovative technologies and products that shape our way of life [1]. However, our current patterns of production and consumption are unsustainable. To address this, future chemists must possess the ability to think holistically and systematically, maximizing resource efficiency while minimizing hazards and pollution. Additionally, it is essential to cultivate citizens who can make informed decisions about science-related policies and their interactions with the planet, based on sound evidence. Including systems thinking approaches in chemistry education is a means of meeting these needs [9].

5. THE RISE OF THE GENERAL SYSTEMS THEORY

Modern systems thinking approaches emerged in the mid-20th century, drawing influences from various fields such as sociology, philosophy, organizational theory, and feedback thought. However, the field of biology played a significant role in shaping the development of systems thinking [10]. Ludwig von Bertalanffy, an Austrian biologist, is widely recognized as the pioneer of systems approaches [11]. In response to the prevailing reductionist approaches in biological research during the early 20th century, Bertalanffy asserted that a comprehensive understanding of organisms requires consideration of both their individual components and their overall structure. He emphasized that organisms possess unique properties, characteristics, and behaviours resulting from the intricate organization and interactions among their parts. Importantly, Bertalanffy emphasized that these emergent properties cannot be solely predicted based on the properties of the individual parts [12].

Bertalanffy's interdisciplinary interests spanned various fields such as chemistry, physics, biology, sociology, and psychology. Through his observations, he recognized that diverse systems within these fields exhibited emergent properties that could not be solely predicted based on an understanding of their individual parts. From these insights, he proposed the existence of underlying rules and principles that govern the emergence of properties at the systems level, applicable across different domains, not limited to biology alone [13]. Concurrently, other researchers were also exploring theories aimed at unifying scientific fields or bridging the gap between natural and social sciences [11]. Notably, individuals like Ralph Gerard, James Grier Miller, Anatol Rapoport, and Kenneth Boulding, with backgrounds in biology, neurobiology, psychology, medicine, and economics, respectively, contributed to the development of these ideas. Boulding, like Bertalanffy, possessed diverse interests and advocated for the significance of alternative perspectives and approaches [12].

6. KEY ASPECTS OF SYSTEMS THINKING APPROACHES

The General Systems Theory, developed by Bertalanffy and his collaborators, deviates from the conventional scientific usage of the term 'theory' as it lacks explanatory capacity. Instead, it functions as an approach for comprehending the intricate nature of our surrounding complex world [12]. Serving as an organizational framework, it aids in the study, research, and understanding of scientific concepts. Bertalanffy proposed that this framework offers a fresh perspective on science, influencing the focal points of scientific research and learning, the methodologies employed in scientific inquiry, and our overall understanding of the nature of science [10]. Science research and learning, guided by a systems thinking perspective, prioritize the following aspects-

- ***Viewing a system holistically:*** Instead of considering a system merely as a collection of individual parts, emphasis is placed on comprehending the system as a whole [9].

- ***Understanding dynamic system behaviour:*** Attention is given to how system behaviour evolves and changes over time, recognizing the dynamic nature of systems [14].

- ***Identifying causal variables:*** The focus is on identifying variables that influence and cause system behaviour, rather than variables that are merely correlated with system behaviour [14].

- ***Exploring system organization and interrelationships:*** Understanding the organization and interdependencies between the various parts of a system is key to comprehending its functioning [9].

- ***Recognizing emergent properties:*** The unique properties that emerge at the system level due to the organization and interrelationships of its parts are considered and studied [10].

- ***System-environment interactions:*** The interaction between a system and its environment, including the human components within the environment, is acknowledged and investigated [10].

- ***Promoting collaboration, democratic participation, and ethical action:*** Systems thinking encourages collaborative efforts, democratic involvement, and ethical decision-making to address complex challenges [9].

A systems thinking perspective in chemistry education involves examining environmental, social, and economic aspects alongside chemical content. Unlike traditional or similar approaches, 'systems thinking' connects chemical knowledge to context and expands learning focus beyond a context-based approach [15]. For instance, following example demonstrates the distinctions in how a systems thinking approach differs from other methods.

A common demonstration in Chemistry involves the exothermic dimerization of NO_2 to N_2O_4, where temperature influences the equilibrium between the two gases. Reductionist approaches in chemistry education simplify and sequence key concepts to facilitate student learning [16]. For instance, a reductionist approach might use the NO_2 dimerization demonstration to teach the challenging concept [17] of chemical equilibrium and provide a reference point for discussing the effects of perturbations on a system at equilibrium [18]. This demonstration supports students' comprehension of complex topics and enhances their learning experience.

An alternative teaching approach involves providing real-world context to enhance the presentation. For instance, an instructor could explain to students that the reddish-brown gas NO2 is a component of photochemical smog, contributing to the brown haze often observed in large cities. Furthermore, they could discuss the link between NO2 formation and the combustion of fossil fuels in vehicles. This context-based approach can be extended through laboratory activities that offer concrete examples related to photochemical smog or fossil fuel combustion. Research has shown that such an approach supports student learning, increases motivation to study chemistry, and fosters relevance and interest by connecting chemical principles to familiar observations and everyday experiences [19], [20], [21].

To explore NO_2 and photochemical smog from a different perspective, a systems thinking approach would be employed. In this approach, the instructor would encourage students to examine how concentrations of NO_2 vary throughout the day in a large city, focusing on the '*dynamic behaviour*' of the system. By adopting a systems thinking mindset, students would analyze the interconnectedness and patterns of change in NO_2 levels, considering various factors that influence its concentration over time.

Upon realizing that NO_2 concentration exhibits a *cyclic behaviour*, with an increase in the first part of the day and a decrease in the latter part, students would be prompted by the instructor to consider the variables that contribute to the fluctuations (*causation*). This line of thinking would involve identifying factors that could elevate or reduce the amount of NO_2. For instance, the instructor might ask students to reflect on variables such as the release of NO from automobile combustion (leading to an increase in NO_2) and the intensity of sunlight (resulting in a decrease in NO_2). By exploring the cause-and-effect relationships between these variables and NO_2 levels, students would gain a deeper understanding of the system dynamics at play [1].

After exploring the chemical interactions that impact the creation and breakdown of NO_2 in photochemical smog, students would be encouraged to ponder the reciprocal relationship between NO_2 levels and human actions. They would be prompted to consider how the quantity of NO_2 could influence human behaviours and, conversely, how human actions could impact the concentration of NO_2. By delving into this interplay, students would gain insights into the potential feedback loops and dependencies between NO_2 and human activities, leading to a more comprehensive understanding of the complex relationship between environmental factors and human behaviour.

The given example illustrates the application of a systems thinking approach, which incorporates discussions on key General Chemistry topics such as reaction rates, equilibrium, thermodynamics, and combustion [1]. It also encourages students to explore the reciprocal relationship between chemical reactions and human actions. The flexibility of the example allows the instructor to adapt the level of guidance given to students based on class constraints. By adopting a systems thinking approach, the instructor can not only provide a contextual understanding of chemistry concepts but also emphasize the causes and time-dependent nature of phenomena.

Moreover, this approach enables considerations of the social, environmental, and economic consequences associated with the phenomenon being studied, offering a more comprehensive learning experience.

7. UNDERSTANDING SYSTEMS AND SYSTEMS THINKING IN PRACTICE

'Systems thinking' encompasses a diverse set of tools and cognitive frameworks that facilitate a comprehensive comprehension of intricate behaviours and phenomena within and across various systems, whether they are natural or artificial. By adopting a holistic perspective, 'systems thinking' enables individuals to perceive higher-level behaviours and phenomena that may not be readily predictable by considering the individual components of a system in isolation. It provides a powerful lens through which the interconnectedness and interdependencies within systems can be grasped, fostering a deeper understanding of complex systems as a whole.

'Systems' exists at various scales, ranging from microscopic to mesoscopic and macroscopic levels. The observer establishes the boundary conditions for a specific system. Each system possesses three essential attributes: (1) components or parts, (2) interconnections among the components, and (3) a purpose. Kim, in his work, outlined several defining characteristics of systems, including purposefulness, the requirement of all parts for optimal functioning, the influence of the arrangement of parts on system performance, and the system's endeavour to maintain stability through feedback mechanisms [22].

'Systems thinking' can be defined as the ability to grasp and interpret intricate systems. It entails visualizing the interconnections and relationships that exist among the various components within a system. Additionally, it involves the examination of dynamic behaviours that unfold and evolve over time. Furthermore, 'systems thinking' delves into the exploration of how phenomena at the systems level emerge as a consequence of the interactions between the system's individual parts [23].

8. DEVELOPING PROFICIENCY IN SYSTEMS THINKING

Systems thinking skills can be understood by examining the distinct abilities demonstrated by a systems thinker. Although various lists of systems thinking skills exist in the literature, there is currently no consensus on the specific skills students should cultivate. Additionally, no chemistry-specific list of systems thinking skills has been developed to date. However, three different perspectives on systems thinking skills offer valuable insights and contribute to the understanding of systems thinking [24]. These perspectives hold the potential to guide the future development of chemistry-specific systems thinking skills and competencies.

Seven Systems Thinking Skills of Richmond

Barry Richmond, an early systems scientist and an influential figure in systems thinking, identified specific skills associated with systems thinking [25]. While originally applied in the context of complex systems in business and management, Richmond acknowledged that these skills could also be utilized to tackle global issues characterized by interdependence, such as ozone depletion, hunger, and poverty [26]. Much of the research on systems thinking in education revolves around Richmond's seven skills, emphasizing their significance. Consequently, it is crucial to explore their potential application in the context of chemistry education. The following section provides a concise explanation of each of Richmond's systems thinking skills. Here is a concise overview of each of the systems thinking skills identified by Barry Richmond-

Dynamic Thinking- While a reductionist approach concentrates on isolated events occurring at a specific moment, dynamic thinking takes a different perspective. Dynamic thinking involves examining how behaviours evolve over time to comprehend the factors that have influenced past behaviours. This understanding enables appropriate adjustments to be made to influence future behaviours effectively [27]. By embracing dynamic thinking, individuals gain insights into the complex interplay of variables and dynamics that shape behaviour, allowing for informed decision-making and proactive interventions.

System-as-Cause Thinking- System-as-cause thinking suggests that it is valuable to perceive the structure of a system itself as the root cause of problem behaviours, rather than attributing these behaviours to external factors. Instead of placing blame on outside agents beyond one's control, system-as-cause thinking encourages individuals to adopt a perspective where they recognize their ability to influence behavior by modifying variables within their system [28]. This mindset shift empowers learners to take responsibility for understanding and adjusting the system's structure, enabling them to exert a meaningful influence on the behaviours exhibited within the system [29].

Forest Thinking- Forest thinking invites individuals to shift their perspective from solely focusing on the individual parts of a system to examining the behaviour of the system as a whole. Instead of analyzing isolated components, forest thinking encourages a holistic view that considers the interconnectedness and dynamics of the entire system. By adopting this approach, individuals gain a deeper understanding of the complex interactions and emergent properties that arise within the system, facilitating more comprehensive analysis and decision-making.

Operational Thinking- Operational thinking prioritizes understanding the causes behind a system's behaviour rather than simply examining variables that are correlated with that behaviour. This approach emphasizes the exploration of how specific variables directly influence and bring about a particular behaviour within the system. By adopting operational thinking, individuals aim to uncover the underlying mechanisms and causal relationships that drive system behaviour, providing a more insightful and comprehensive understanding of the system dynamics.

Closed-Loop Thinking- A significant portion of reasoning used in science education and research can be categorized as 'straight line thinking'. This approach focuses on analyzing the direct impact of one variable on another variable [25]. However, closed-loop thinking offers a broader perspective by recognizing that the relationship between variables is not unidirectional. It acknowledges that while variable 1 may influence variable 2, variable 2 can also affect variable 1. In closed-loop thinking, the interactions and feedback between variables are taken into account, leading to a more comprehensive understanding of the complex relationships and dynamics within a system.

Quantitative Thinking- According to Richmond, although not all variables can be measured directly, they can still be quantified on a relative scale [25]. For instance, values can be assigned to represent the level of commitment to a project, with 100 indicating complete commitment and 0 indicating no commitment. Systems thinkers go beyond identifying interrelationships between the components of a system. They also strive to quantify these interrelationships and understand how they contribute to observed system behaviour. By quantifying the interrelationships, systems thinkers gain a more precise understanding of the dynamics and influences within the system, enabling more accurate analysis and predictions.

Scientific Thinking- Systems thinkers engage in developing models that describe the interrelationships among the components of a system and their contributions to system-level behaviours. Based on these models, hypotheses are formulated. Scientific thinking encompasses the rigorous testing of these models and hypotheses through virtual or physical experiments. This iterative process of modelling, hypothesis formulation, and experimentation allows systems thinkers to refine their understanding and gain insights into the complex dynamics of the system under investigation [25].

Systems Thinking Hierarchical Model

While Richmond's list of systems thinking skills was pioneering, it has certain limitations when considering their suitability in the context of chemistry education. Firstly, these skills were not initially intended for application in science education. Secondly, they lack empirical derivation. To overcome these limitations, the Systems Thinking Hierarchical Model offers a solution. This model takes into account both the specific needs of chemistry education and the empirical grounding of skills, providing a more comprehensive and tailored framework for developing systems thinking skills in the context of chemistry.

Assaraf and Orion identified eight distinct systems thinking skills, which share similarities with Richmond's systems thinking skills. They also observed that these skills were developed in a hierarchical and sequential manner, with the attainment of lower-level skills being a prerequisite (though not the sole requirement) for progressing to higher-level skills. The ordered list of skills proposed by Assaraf and Orion is known as the '*Systems Thinking Hierarchical Model*' (STH Model) [30]. This model provides a structured framework for understanding and cultivating systems thinking skills, offering a pathway for students to develop their abilities in a step-by-step manner.

The Systems Thinking Hierarchical Model (STH Model) organizes the eight systems thinking skills into three distinct levels: analysis of system components, synthesis of system components, and implementation [31]. Starting from the bottom level, the analysis of system components focuses on the first systems thinking skill, which involves identifying the components and processes within a system. Moving up to the second level, synthesis of system components, four skills come into play. These skills include identifying relationships among system components, recognizing dynamic relationships within the system, organizing components and processes within a relational framework, and understanding the cyclic nature of systems. At the top of the model, the third level, implementation, encompasses the final three skills: making generalizations, understanding the hidden dimensions of systems, and thinking temporally through retrospection and prediction. This hierarchical structure provides a framework for developing systems thinking skills, guiding learners through a progressive journey towards more advanced and comprehensive systems thinking abilities.

In the context of chemistry education, it is noteworthy that the Systems Thinking Hierarchical Model (STH Model) incorporates "understanding the hidden dimensions of the system" as a higher-level systems thinking skill [30], [31]. Considering that chemistry encompasses numerous hidden parts and processes, it becomes crucial to explore effective approaches for assisting students in accessing and comprehending these hidden dimensions during their engagement in systems thinking. By addressing the hidden aspects of chemical systems, educators can facilitate a deeper understanding of the complexities involved, enabling students to develop more comprehensive and nuanced systems thinking abilities within the field of chemistry.

9. SUMMARY

This study has outlined the origins and characteristics of systems thinking while introducing the skills commonly employed by systems thinkers. 'Systems thinking' serves as a valuable complement to reductionist approaches in both chemistry and chemistry education. By adopting systems thinking, current and future chemists, as well as global citizens, can perceive chemistry not merely as a subject to be learned and studied, but as a powerful tool for tackling the intricate global challenges faced by society today. 'Systems thinking' offers a fresh perspective that empowers individuals to utilize chemistry as a means to address complex issues and contribute to positive societal change.

'Systems thinking', as a complement to reductionist approaches, has the potential to bring about profound transformations in the way we practice, teach, and learn chemistry. By embracing systems thinking, chemists can envision new possibilities and developments in their field. It raises intriguing questions: How might chemistry, chemistry education, and the roles of chemists themselves is altered? What novel chemical discoveries and methodologies might arise? What innovative applications of chemistry could emerge to address global challenges? Furthermore, 'systems thinking' prompts a re-evaluation of chemists' responsibilities towards the planet and its inhabitants, as well as a shift in the perception of chemistry's purpose and outcomes by students and society at large. Considering the positive outcomes observed in other disciplines, it is imperative to explore how systems thinking can catalyze similar transformative effects in both chemistry and chemistry education.

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BIOGRAPHIES

Prof. Manoj K S Chhangani dedicates his research endeavours to promote innovation in higher education. He delves into various aspects of this domain, striving to discover fresh methodologies and practices that can elevate the learning process. Additionally, he plays an active role in exploring the realms of green chemistry and waste management, with the ultimate goal of devising sustainable approaches to pave the way for a greener future.

Prof. Sofia I. Hussain, a committed educator, focuses her research on investigating modernism in higher education, delving into its diverse facets. Furthermore, she devotes significant attention to the fields of green and sustainable chemistry, actively exploring innovative approaches and practices that foster environmental consciousness and sustainable development.