

Teaching catalysis as a means to enhance scientific literacy amongst chemistry students in Dutch secondary education

An explorative investigation

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Abstract

In order to develop scientific literacy, students should be encountered with relevant teaching material that is true to nature to the field of practice as it is today. Comparing a conceptual framework with an analysis of current Dutch teaching methods in secondary chemistry education showed that an incoherence has occurred between the fragmented and thin approach to the concept of catalysis relative to the important factor it plays in the field of research. In an attempt to minimize the mismatch between these aspects, prototypical educational material on the fundamental concepts of different types of catalysts has been developed and tested in a design based research in natural classroom setting. Using the jigsaw method, students were assigned to write an advisory report stating if either a heterogeneous-, homogeneous- or biocatalyst was most suitable to be used in the decomposition of hydrogen peroxide. The reports consisted of statements regarding one of five catalytic aspects: activity; availability; safety; stability and recovery, written in the style of Toulmin's model of argumentation. Along with these statements, written answers on questions in the module and a short interview were used for qualitative data processing by means of open coding. Achieved learning outcomes were drawn up and compared to the intended outcomes. The module was found to be effective in developing conceptual understanding around the aspect of activity. Although discovering some misconceptions of several groups interpreting the following statement the wrong way around, most groups made correct statements such that a catalyst is most suitable to be used if it decreases more of the initial activation energy of the reaction. Though other aspects did not result to the intended outcomes, the exploratory module could be a useful start to a catalysis centralized approach which enables students to gain an in-depth conceptual understanding of the domain of catalysis and thereby becoming more scientific literate.

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Introduction

Fundamentals of the chemistry curriculum

One of the main reasons of teaching science in secondary education is to enhance scientific literacy amongst students. At macroscale, scientific literacy enhances support for science as well as enabling students to participate more intelligently in, or even influence, debates around social scientific issues. At microscale it has been stated that individuals benefit greatly being scientific literate (Laugksch, 2000). In order to reach its goal of enhancing scientific literacy amongst students, the curriculum should be true to nature of the field of chemistry as it is today. It provides students with more relevant teaching material, enables them to form an idea of how science is established into our society and it facilitates an easier selection process for future career paths.

The threat of curriculum misalignment

In light of chemistry's assimilation into, and collaboration with nearly all scientific and technological endeavors, a reexamination of the domain's structure has suggested a current description of what chemists do. The resulting description contained three main aspects, being: explaining natural phenomena, analyzing matter to determine its chemical makeup and synthesizing new substances (Evans et al., 2006). A well-developed curriculum must fully cover these three main aspects with an integrative learning experience. Then, the curriculum can be described as 'a means of inducting the student into disciplinary practices such that they can, if they wish, progress from student to master' (Parker, 2003). For those involved in curriculum development there is a minimum need to balance industrial/market needs with the perspective of pedagogic integrity (Hatzakis et al., 2007). An imbalance between these two areas of concern leads to a phenomenon called *curriculum misalignment* occurs. Two types of misalignment can occur: For example, if a curriculum leans too much into the industrial/market needs, a potential incoherence between the intended curriculum, the implemented curriculum and/or the attained or experienced curriculum is at risk. On the other hand, if a curriculum leans too much into the perspective of pedagogic integrity, a potential mismatch between the field of science and the curriculum that is being used in education is under threat. These mismatches should be held to a minimum as it is not the intention that students are missing out on authentic scientific activity and therefore gaining misleading impressions about the work that scientists do (Hume & Coll, 2010).

Potential curriculum misalignment in current chemistry curricula

For chemistry education in particular, the current syllabus teaches students about the subfields of analytical, biochemical, inorganic, organic, physical and theoretical chemistry. However, one could argue if the curriculum is still up to date. For example, a major part of the curriculum of organic chemistry still revolves around classic fossil-fuel based chemistry, while the field of research has already shifted its focus to much more comprehensive and more sustainable energy adaptations with the help of catalysts. Catalysts provide chemists with alternative reaction mechanisms enabling lower activation energies, therefore contributing to the pursue of accomplishing several of the United Nations' Sustainable Development Goals (SDG's). Two examples are: SDG 7, affordable and clean energy, with research on CO₂ conversion and SDG 12, responsible consumption and production, with research on biomass as a source for chemicals rather than crude oil (United Nations, 2015, 2020). By underexposing the impact of catalysis on the chemical industry, while at the same time relying on mostly outdated classic fossil-fuel based chemistry, a potential curriculum incoherence has occurred. In this case the focus had shifted too much to the perspective of pedagogic integrity, oversimplifying the curriculum with the intention to keep it manageable for students, at the expense of losing connection with the chemical industry/market in the process.

Attempting to re-obtain coherence by curriculum development with catalysis as key concept

The contradiction is, that while catalysis is a renowned research field in both industry and research, many concepts of catalysis are not at all, or only briefly, discussed in secondary chemistry education. Besides that, catalysis is fragmented over several topics in the curriculum, with the result that students are unable to see coherence in the topic. Partly because of this, an extensive process has been initiated in order to make the curriculum future-proof. This process, called 'Curriculum.nu', invited representatives of teachers, school leaders, school boards, scientists, teacher educators, higher education, teacher unions, students and parents to prepare proposals on how the curriculum could be improved. These proposals do not only mention the fact that it is favorable to have short connections with the working field of universities and corporations, which obviously leads to the fact that it is important that the connection between the two is coherent, it also expresses the wish to lay emphasis on sustainability, which also goes hand in hand with the focus of research in the field of chemistry (Curriculum.nu, 2019).

Research focus

Could a shift in the approach of Dutch secondary chemistry education, where students receive introduction to common issues in the current field of research through the principles of catalysis, enable for a more coherent and true to nature chemistry curriculum? In this study, as an attempt to form an answer to this question, three consecutive steps, related to the field of catalysis, are conducted. The first step is to construct, by extensive literature review, a conceptual framework of catalysis throughout several stages of chemistry education. The second step is to analyze the current state of catalysis teaching in the secondary chemistry curriculum, from the viewpoint of this framework, by reviewing Dutch chemistry learning methods. These first two steps eventually lead to the third step and main focus of the research, which is to design a prototypical teaching module in which students are introduced to a more true to nature view of the field of catalysis. The resulting design is empirically tested for learning outcomes in a classroom setting. The collected learning outcomes contribute to the aim of this research, being the investigation to which extend the explorative teaching design helps students gain insight in the field of catalysis as an important and relevant domain of the field of chemistry.

Theoretical background

In order to gain a detailed overview of the topic of catalysis, at first it is necessary to dive into the history and take a closer look at the origin and subsequent growth of catalysis as research field. Secondly, the importance of catalysis in chemical related industries nowadays is sketched. At last, a step to chemistry education is being made, elaborating the way the concept of catalysis is treated in curricula from secondary to higher education in general and Dutch secondary education in particular.

Catalysis: from first observation to a renowned research field

Dating all the way back to 1835, at times when it was still possible for one man to prepare the annual report of the progress of chemistry research as a whole, Jönz Jacob Berzelius reviewed a number of earlier findings on chemical change in both homogeneous and heterogeneous systems. Based on these findings he introduced the concept of catalysis and summarized his ideas as follows: *“It is, then, proved that several simple or compound bodies, soluble and insoluble, have the property of exercising on other bodies an action very different from chemical affinity. By means of this action they produce, in these bodies, decompositions of their elements and different recombinations of these same elements to which they remain indifferent”* (Berzelius, 1836). Berzelius proceeded to propose the existence of a new force which he called the ‘catalytic force’ and he called ‘catalysis’ the decomposition of bodies by this force. This was probably the first recognition of catalysis as a wide-ranging natural phenomenon. (Robertson, 1975).”

The area of catalysis quickly advanced and intensive research eventually led to a new understanding about the fundamental understanding of catalysis. In 1894, Friedrich Wilhelm Ostwald and others considered that *“catalyzed gas reactions resulted from the absorption of gases in the cavities of the porous metal, where compression and local temperature elevation led to chemical combination”* (Ostwald, 1894). Ostwald believed that a heterogeneous catalyst did not induce a reaction but rather accelerated it without formation of intermediate compounds. In other words, a catalyst was a body that modified a reaction without taking part in it. The assumptions of Ostwald led to the 1906 Nobel Prize in Chemistry, but Paul Sabatier did not accept this purely physical view of the function of the catalyst. The remark was that, if the assumptions Ostwald made were true, then charcoal should be almost a universal catalyst, which it was not. The physical theory was unable to explain the development of high local pressure and temperature in the cases where the catalyst was held in suspension, and did not account for the specificity of catalysts and the remarkable diversity of effects they produced, depending on the particular metal of oxide used (Sabatier, 1897, 1913). Sabatier then formulated a more chemical theory of catalysis involving the formation of unstable chemical compounds as intermediate stages, which determined the direction and rate of the reaction. He also argued that the formation and decomposition of intermediate compounds usually corresponds to a diminution of the Gibbs energy of the system (Sabatier, 1913; Wisniak, 2010).

The impact of catalysis

The research by Sabatier and his students, led to the discovery that many metals, particularly nickel and the platinum group elements, alone or supported, possessed a unique catalytic activity, especially for hydrogenation reactions (Wisniak, 2010). It was discovered that the presence, and the presence alone, of hydrogenation metal catalysts such as nickel made it possible to fix hydrogen on the most various molecules. This resulted to winning the 1912 Nobel Prize in Chemistry and would ultimately become the base for the fast development of the petrochemical industry. The impact of catalysis and catalysts remains to be substantial.

In current times, catalysis plays a key critical role in shaping the future of areas such as chemical and energy production. Besides playing a role in many environmental technologies and dynamically addressing societal challenges, catalysis is one of the utmost cross-cutting and key enabling disciplines in chemical industry. Catalytic materials are crucial to reduce today's and future environmental burdens and can help to make products more environmentally benign and sustainable, to reduce CO₂ emissions, or to address future energy challenges. Catalysis and catalytic processes account directly or indirectly for about 20 to 30% of the world's gross domestic product (GDP). Also, the manufacture of catalysts has a large economic impact, since the global catalyst market is expected to reach 34.3 billion US\$ by 2024. Of the 50 largest volume chemicals currently produced, 30 are produced via catalytic routes. These 50 highest volume processes account for more than 20 billion tons of carbon dioxide. Technical improvements in catalyst and related process could reduce energy intensity for these products by 20 to 40% as a whole by 2050. In absolute terms, improvements could save as much as 13 EJ (exajoules) 1 Gt (gigaton) of carbon dioxide equivalent per year by 2050 versus a "business-as-usual" scenario (Perathoner et al., 2017).

Catalysis as part of the chemistry curriculum

Whereas research in catalysis flourishes on a truly global scale, scholarly studies that address education in catalysis are hard to find. Only since the early 1990s, Germany started working on a curriculum for higher education courses called 'Lehrprofil Katalyse', the document has been updated ever since (Armbrüster et al., 2018). Other countries also emphasized the need for establishing new courses throughout the world focusing on heterogeneous catalysis for the biorefinery encompassing many different fields in a multidisciplinary approach.

In the past, however, catalysis education has had some issues. One issue was, much like the discussions between Ostwald and Sabatier, that catalysis education has been wrongly defined in the past. For example, as early as 1946, James Arthur Campbell described in the Journal of Chemical Education that twelve chemistry textbooks wrongly defined catalysts "*as substances which alter the rate of a chemical reaction but are not themselves permanently changed*", when Campbell continued, "*a catalyst is a substance which affords a new mechanism for the reaction with no change in the chemical composition of the catalyst, though the catalyst actually undergoes permanent change*" (Campbell, 1946). Only four decades later, the International Union of Pure and Applied Chemistry (IUPAC) defined a catalyst as "*a substance that increases the rate of a reaction without modifying the overall standard Gibbs energy change in the reaction*" being "*both a reactant and product of the reaction*" (Pagliaro, 2021). Another issue in catalysis education has been the separation of the traditional domains of chemistry, being organic, inorganic, physical, analytical, bio and sometimes also polymer chemistry. The in-depth concepts catalysts bring to each different domain can be rather advanced when the curriculum is taught from the foundation-level. However, catalysis education may be the key topic in developing interest in hybrid and interdisciplinary approaches to the chemistry curriculum, enabling students to be exposed to a variety of domains, such as organic-, inorganic- and biochemistry (Schaller et al., 2015). Shown in Figure 1 is an overview of the conceptual framework of catalysis, along with a brief overview on each concept.

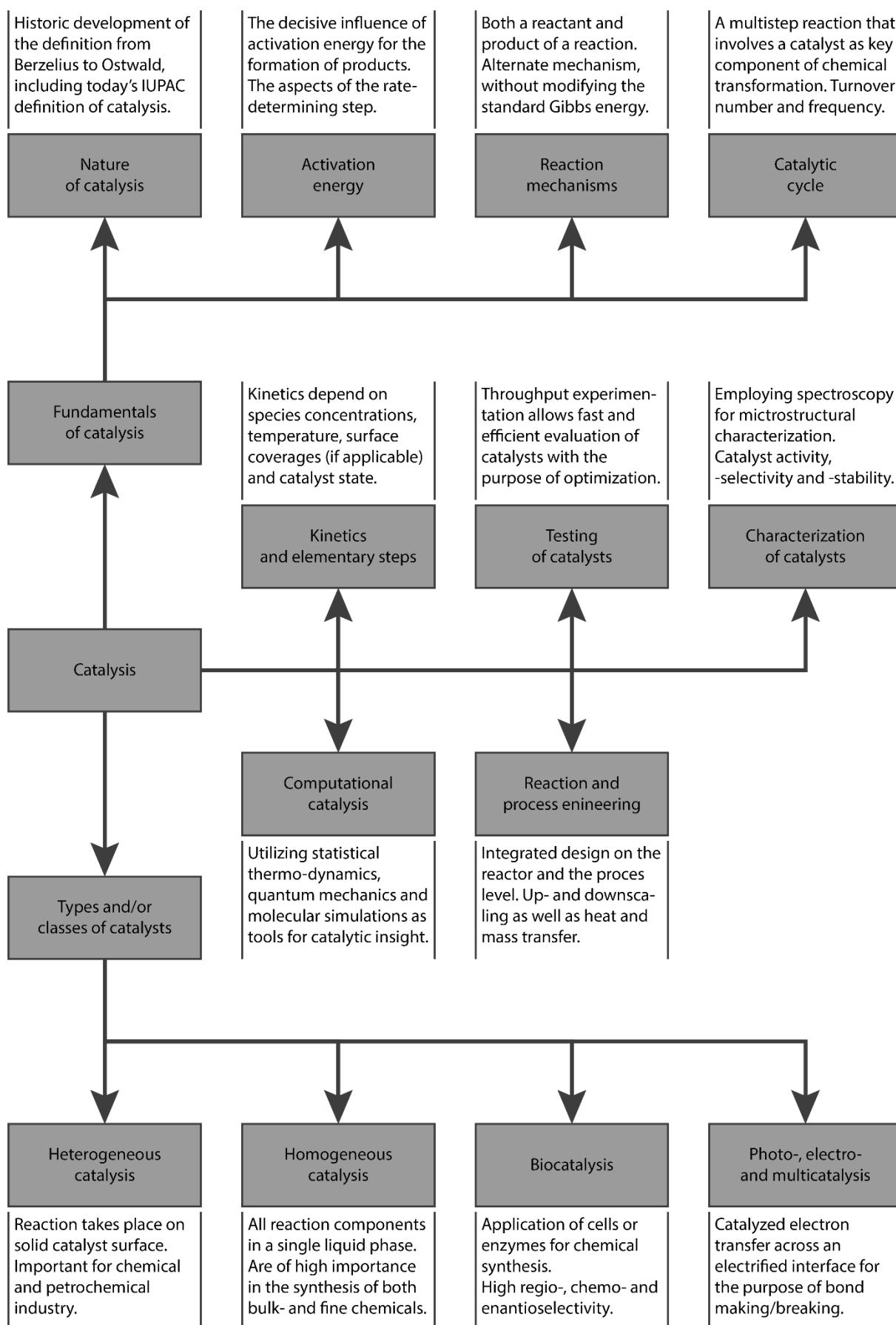


Figure 1: Conceptual framework of catalysis education from secondary education up to higher education, as described by (Armbrüster et al., 2018).

Teaching method analysis of the Dutch secondary chemistry curriculum

Building on the elaboration of catalysis as research field and proposed definitions, as well as the major goals of catalysis education, we are able to evaluate to what extent the current learning goals on catalysis in the Dutch chemistry curriculum are conform literature standards. Therefore, an analysis on Dutch chemistry teaching methods has been performed using three popular teaching methods: 'Chemie' and 'Chemie Overal' from publisher Noordhoff and 'NOVA' from publisher Malmberg. The target audience of these methods all focus on students in higher secondary education. Within each method, textbooks were written for 'VWO-students', as shown in Table 1.

Publisher	Teaching method	Class / Domain	Edition / Press	Year	ISBN
Noordhoff Uitgevers	Chemie	3 VWO	6 th edition	2013	9789001828707
		4 VWO	6 th edition	2012	9789001817107
		5 VWO	6 th edition	2014	9789001817176
		6 VWO	6 th edition	2015	9789001817190
	Chemie Overal	3 VWO	6 th edition	2010	9789011111226
		4 VWO	4 th edition	2012	9789011113794
		5 VWO	4 th edition	2014	9789011113800
		6 VWO	4 th edition	2015	9789011113831
Malmberg	NOVA	3 VWO Gymnasium	4 th edition	2018	9789402058321
	NOVA MAX	4 VWO Gymnasium	3 rd press	2019	9789402058291
		5 VWO Gymnasium	1 st press	2018	9789402013122
		6 VWO Gymnasium	4 th press	2019	9789402013139

Table 1: Descriptions of the books used for the teaching method analysis.

All methods were analyzed only within the topic of catalysis and corresponding topics such as kinetics or the reaction mechanism. Each time a concept within the conceptual framework of Figure 1 was mentioned, it was administrated. A list of concepts sorted by year is found in Table 2.

Grade	Concept	Chemie	Chemie Overall	NOVA
9	Biocatalysis	x	>	>
	<i>As Chemie depicts the curriculum mostly from a context-concept perspective, the concept of biocatalysis is introduced as enzymes are mentioned as supplements of laundry detergent.</i>			
	Rate of reactions	x	x	x
	<i>In each teaching method, the first real introduction from the concept of catalysis comes forth from the domain of kinetics. These methods teach four factors to influence the rate of a reaction, one of which is adding a catalyst.</i>			
	Definition circumscribed	x	x	-
	<i>During the third class, the definition of a catalyst in most of the teaching methods is limited to a description much like Ostwald's: being that a catalyst accelerates a reaction without being used. A further explanation of how this phenomenon works is not given yet in the methods published by Noordhoff Uitgevers.</i>			
10	Definition extensive (by introducing the concept of activation energy)	>	>	x
	<i>In ninth grade, NOVA further extends the concept of catalysis to a description much like Sabatier's. Explaining that a catalyst diminishes the activation energy of a reaction, therefore facilitating a faster reaction process.</i>			
	Biocatalysis	<	x	>
	<i>Chemie Overall describes enzymes as catalysts that accelerate biological reactions.</i>			
	Catalysts in equilibria	x	x	x
	<i>As catalysts accelerate both directions of a reversible reaction, it does not affect the position of an equilibrium. But since the methods mostly portray the concept of equilibria as an extension of the concept of rate of reactions, all four factors of reaction rate are covered.</i>			
11	Heterogeneous catalysis	-	-	x
	<i>NOVA briefly covers the difference between a heterogeneous and homogeneous catalyst. And continues to depict a detailed example of heterogeneous catalysis by means of the Fischer-Tropsch reaction.</i>			
	Biofuels	-	-	x
	<i>NOVA combines the topic of biofuels together with classic refining of fossil fuels and therefore enrich the topic of organic chemistry to a more sustainable perspective.</i>			
	Mechanisms	>	x	x
	<i>For all methods, reaction mechanisms is introduced between classic topics between organic chemistry, such as addition and condensation, and advanced topics such as biochemistry/polymer chemistry. As catalysts play a weighted part in a reaction mechanism, it is no surprise that this concept relies heavily on the topic of mostly homogeneous catalysis.</i>			
12	Homogeneous catalysis	-	-	x
	<i>After the introduction of reaction mechanisms, NOVA proceeds to introduce homogeneous catalysts by teaching about how catalysts influence the reactivity of a substrate.</i>			
	Photocatalysis	-	-	x
	<i>In some additional material, NOVA reviews the use of titanium(IV)oxide (TiO₂) as a photocatalyst. Stating many possible applications under which the use of TiO₂ in paint to facilitate sterile rooms.</i>			
	Biocatalysis	<	<	x
	<i>In all three methods, biochemistry is only taught in twelfth grade, as detailed as teaching the four structural degrees of enzymes. Chemie and Chemie Overall have mentioned definitions of enzymes earlier in their methods, NOVA chose to introduce this concept later.</i>			
12	Mechanisms	x	<	<
	<i>For all methods, reaction mechanisms is introduced between classic topics between organic chemistry, such as addition and condensation, and advanced topics such as biochemistry/polymer chemistry. As catalysts play a weighted part in a reaction mechanism, it is no surprise that this concept relies heavily on the topic of mostly homogeneous catalysis. Chemie is the only method which chose to introduce mechanisms in the twelfth grade.</i>			
	Catalyst stability	x	x	x
	<i>All three methods focus their perspective on catalyst stability in the domain of biocatalysis. It is stated that enzymes have specific temperature- and pH-optima which influence the effectivity of the enzyme.</i>			
	Catalyst selectivity	-	-	x
	<i>NOVA describes that catalysts not only manage to accelerate a reaction, but also enable some specific reaction paths leading to more selective reaction products.</i>			

Table 2: Conceptual framework of catalysis within Dutch secondary chemistry education. An 'x'-symbol indicates that the specific concept is taught in the method from that year onwards; the '-' symbol indicates that a certain concept is completely absent in the full teaching method. A '<' or '>' symbol indicated that a certain concept is taught in the method, but earlier or later respectively.

General similarities amongst methods: learning trajectory on catalysis

While these three teaching methods obviously differ slightly from one another, a general learning trajectory throughout the four years of the chemistry course can be depicted. The resulting trajectory is shown in Figure 2.

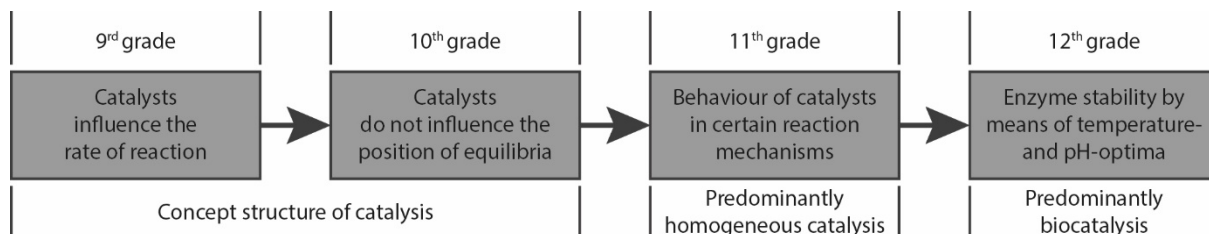


Figure 2: General learning trajectory of catalysis in Dutch secondary education.

Somewhat understandable, the first two years of the course comprise a somewhat rudimentary view on catalysis. Students get in touch with catalysis quite early in the course, as early as the third class, through the topic of kinetics. Revolving from the rate of reactions, they learn about the following four different factors which influences the reaction rate: temperature, concentration, degree of distribution and catalysis. The introduction is quite brief and, although it is probably limited on purpose to account for student developmental levels, it may even be deemed incorrect according to the actual knowledge of the specific scientific subject area (Devetak & Vogrinc, 2013), since the proposed definition of a catalyst may lean a bit too much to the outdated definition of Ostwald. In the fourth class, the kinetic-based approach continues when students learn that some reactions appear to be reversible. As catalysts accelerate both directions of a reversible reaction, it does not affect the position of an equilibrium. But since the methods mostly portray the concept of equilibria as an extension of the concept of rate of reactions, all four factors of reaction rate are covered.

The last two years of chemistry education comprise a more enriched view on catalysis. At first, mostly induced from the concept of reaction mechanisms, the detailed interaction between a catalyst and a substrate is being reviewed. This entails mostly homogeneous catalysis, since aforementioned catalysts tend to make covalent bonds with a substrate, thereby changing the electron distribution of the molecule making it more nucleophilic or electrophilic depending on the catalyst and substrate used. Heterogeneous catalysts do not lend themselves for this type of topic since the interaction between heterogeneous catalysts and substrates are more often different from the types of bonds students are familiar with. Secondly, since biochemistry takes up a large share of the twelfth grade topics, students learn in detail how the four different degrees of structure of enzymes leads to the formation of active sites which themselves achieve catalytic action by binding substrates to the active site via van der Waals interactions, hydrogen bonds or ionic bonds. They also learn that enzymes have different levels of activity according to the temperature or pH-value, stating that large deviations from the optima can lead to denaturation, the loss of the secondary, tertiary and quaternary structure of the enzyme.

In conclusion, it can be stated that the first years of Dutch chemistry education are used to build up a shallow concept structure of catalysis while its last years are used to focus on several more in-depth topics such as interactions of homogeneous catalysts to substrates and catalyst stability amongst enzymes. The lack of in-depth topics where heterogeneous catalysts flourish is something that is remarkable, due to its large share in industrial chemistry. The leading effect is that the remaining topics within the field of catalysis are somewhat fragmented across the curriculum.

Several differences between methods

Besides the general similarities between the methods, it is also worth mentioning several differences between the three. One observation that stands out from the rest is the fact that, looking at the number of concepts on catalysis, NOVA manages to be the most comprehensive teaching method on this concept framework. Besides just building up the concept framework on catalysis; the method includes several additional teaching materials where the boundaries of the conceptual framework of catalysis are pushed beyond the topics of heterogeneous-, homogeneous- and photocatalysis as well as the concept of biofuels and catalyst selectivity. An example of this is shown in an introductory paragraph in the fourth class before the concept of kinetics is taught. This introductory chapter starts with a brief history on the discovery of catalysts and the early applications of this phenomenon, such as Döbereiner's lamp, followed by a disquisition on the deployment of the Fischer-Tropsch (FT) process during times of oil scarcity. This topic, which relies heavily on the concept of heterogeneous catalysis, is then further expanded to the Biomass-to-Liquid (BtL) process and the variety of possible elements that are able to catalyze the reaction, appointing several pros and cons of each element regarding aspects of catalyst stability, -selectivity, -activity and availability (mostly expressed as a financial factor). The chapter hits the right notes on several important didactical factors: such as presenting the beforementioned aspects with adequate, qualitative introductions (Gabel, 1983; Ruis, 1988) and integrating textual elements with visual elements (Devetak & Vogrinc, 2013; Gegios et al., 2017; Gkitzia et al., 2011). This example can therefore be designated as a good practice enabling students to the current industrial field and field of research, and it would be recommended to stimulate or expand these types of context-concept approaches between modern day chemistry and the chemistry curriculum for future curriculum developments.

Contexts

In-depth conceptual understanding of science subject matter advocated in the various visions of reform can only be reached in a context-rich learning environment. These contexts within the topic of catalysis help create students that can be considered scientifically literate (Lederman, 1999). Therefore, consecutively to mapping the different concepts present within textbooks, the associated contexts have also been categorized, according to the types/classes of catalysts in which the context belongs. It is remarkable that catalysts as part of heterogeneous production processes are most common amongst the three teaching methods, while that type of catalysis is the least apparent in the general learning trajectory. The second most common catalyst type that is found in contexts is the biocatalyst. The accompanying, and wildly diverse, contexts are used to illustrate the concept structure of catalysis as well as the in-depth theory on enzyme stability. The full list of contexts is shown in Table 3.

Concept	Context	Chemie	Chemie Overall	NOVA	
Heterogeneous catalysis	Car exhaust	x	x	x	
	<i>The use of catalytic converters in cars with the intention to break down the pollution of exhaust gases using a catalyst.</i>				
	EVAC+	-	x	-	
	<i>The use of catalytic conversion in evacuation masks with the intention to convert carbon monoxide into carbon dioxide using a catalyst.</i>				
	DeNO _x installations	-	x	-	
	<i>The use of catalytic conversion in coal-fired power stations where a catalyst is used to convert nitrogen oxide containing flue gases into nitrogen and water using ammonia.</i>				
	Haber Bosch proces	x	x	x	
	<i>The presence of a catalyst is of importance during the Haber Bosch proces, where ammonia is synthesized from hydrogen and nitrogen.</i>				
	Catalytic reforming	x	x	x	
	<i>A chemical process in which petroleum refined naphthas are converted into high-octane reformates.</i>				
	Other chemical production processes	x	x	x	
	<i>Several production processes which rely on the use of heterogeneous catalysts are mentioned. Such of methanol production which uses a copper catalyst; aminobenzene production which is possible through the Béchamp or Dow proces or the production of nitric acid which uses a platina catalyst.</i>				
	Fischer Tropsch proces	x	x	x	
<i>A comprehensive description of how different possible catalysts are used to convert syngas into hydrocarbons.</i>					
Lamps	x	-	x		
<i>Several contexts of hetrogeneous catalysis in lamps are mentioned. Such as Döbereiner's lamp or the Davy lamp, which was created to reduce the danger of explosions due to the presence of flammable gases.</i>					
Fuelcells	x	-	x		
<i>Several fuel cells are described, as well as the aspect of catalyst poisoning.</i>					
Homogeneous catalysis	Biofuel	x	x	x	
	<i>During the production of biodiesel, molecular catalysts are used to increase transesterification.</i>				
	Condensation reactions/condensation polymerization	x	x	x	
	<i>Acids act as catalysts in the reaction mechanism of a condensation reaction.</i>				
Ethylbenzene production	x	-	-		
<i>During the synthesis of ethylbenzene from benzene and ethene, an acid catalyst is used.</i>					
Biocatalysis	Fruit	-	x	-	
	<i>The enzymatic process of food browning.</i>				
	Escherichia coli	-	x	-	
	<i>E. coli manages to break down tough stems and leaves of plants using a particular enzyme.</i>				
	Digestive systems in humans or animals	x	x	x	
	<i>Several enzymes that fulfill a part in our digestive system are being mentioned. Such as lipase, alcohol dehydrogenase or carbonic anhydrase.</i>				
	<i>CK1e can possibly be influenced in order to reduce the effect of jetlags.</i>				
	<i>The citrus mealybug is known to incorporate two types of bacteria into its body. These bacteria produce essential enzymes which the citrus mealybug cannot produce itself.</i>				
	<i>The bombardier uses a mixture of enzymes to produce the irritating compound quinon from hydrogen peroxide and phenol. The animal uses this fluid as a matter of defense.</i>				
	<i>The mad cow disease changes the secondary and tertiary structure of prion proteins, causing enzymes to disfunction.</i>				
<i>Patients with phenylketonuria are missing the enzyme phenylalaninehydroxylase.</i>					
Biochemical technology	-	x	-		
<i>Modification of plasmids can be used to our advantage in order to produce biobased resources.</i>					
Laundry detergent	x	-	x		
<i>Use of enzymes in laundry detergents with the intention to remove food stains.</i>					
Photo-, electro- and multicatalysis	Ecopaint	-	x	x	
	<i>The use of titanium(IV)oxide in paint with the intention to convert nitrogen oxide from polluted air into nitric acid. This catalytic conversion only proceeds in the presence of UV-light.</i>				

Table 3: Corresponding contexts per concept of catalysis in Dutch secondary chemistry education.

Converging research focus into aim and research questions

In comparing the teaching method analysis to the conceptual framework, it is now clear that the current Dutch secondary chemistry curriculum offers too little for students to gain an in-depth conceptual understanding of the concept matter of the field of catalysis. With one of the causes being the fact that the topic of catalysis is only offered in fragmentation amongst the curriculum. This is undesirable since it deters students from gaining a coherent perception about catalysis. The other cause is the fact that the curriculum lacks several concepts that are important within the field of chemical industry, a significant example being heterogeneous catalysis. Due to this misalignment between the curriculum and the nature of the field of science, students fail to form a correct idea of how science is established as well as what a future career path in chemistry could look like.

This leads to the aim of this research, in which a prototypical teaching module is designed which introduces students in secondary education to a more true to nature view of catalysis. Providing students with more relevant teaching material and thereby enhancing scientific literacy. Testing the design in a natural classroom setting, thereby collecting student learning outcomes, enables for an investigation on how this explorative module helps students to gain insight in the field of catalysis as an important and relevant domain of the field of chemistry. The accompanying research question is as follows:

To what extent does the explorative teaching module, that combines the topics of homogeneous-, heterogeneous- and biocatalysis, enable students in secondary chemistry education to gain an in-depth conceptual understanding of the topic of catalysis?

In an attempt to answer the abovementioned research question, this study could contribute to future curriculum developments, thereby enhancing scientific literacy amongst students in secondary education by reducing the incoherence between the field of catalysis and the intended curriculum.

Experimental methodology

Preparing modules on catalysis for implementation

In earlier attempts to update the current Dutch chemistry curriculum to the modern standards of the industrial field, at least for the topic of catalysis, Utrecht University has made a few attempts to design educational materials for the target audience. One of these prototypical modules is called 'Katalyse: kernbegrip in de chemie' (translated: 'Catalysis: core concept in chemistry'). This module, initially written by Ton Bominaar (Zernike College); Gjalt Prins and Maaïke Pol (Freudenthal Institute, Utrecht University) (Bominaar et al., 2019), has been used as basis for a new prototypical module, called 'Determination of the activation energy of a catalyzed decomposition' (translated: 'Activeringingsenergie bepalen van een gekatalyseerde ontledingsreactie'). This new module, which is attached to this document as Appendix A, has been written with two design requirements in mind. The first requirement was that, in order to evade the fragmentation of the topics in teaching methods, several contexts from the conceptual framework on catalysis had to be combined into one module. The second requirement was that the module contained experiments for a natural classroom setting, to accentuate the empirical approach of catalyst research.

The requirement for centralization of the topic of catalysis was reached by setting up an assignment in the context of a chemical industrial process, in which students fulfilled the role of a Research and Development department for a large chemical business. The module combined several different concepts that are found in the conceptual framework, being the fundamentals of catalysis and three different types of catalysis: homogeneous-, heterogeneous and biocatalysis. The remaining concepts of the framework, like characterization of catalysts and computational catalysis, are probably too complicated for secondary education and are better fit for courses in higher education. As a method to construct the module around the desired concepts, students are introduced to five independent catalyst aspects, such as: catalyst activity, -availability, -recovery, -safety and -stability. Like in NOVA's introductory chapter on 'Biomass to Liquid Fischer Tropsch processes', different types of catalysts prove to have their own pros and cons regarding these certain aspects. Therefore, the aim is that in regarding these five aspects of catalysis, students are learning about its fundamental properties. Furthermore, through combining the three beforementioned different catalyst types, the module aims for students to learn about certain differences/similarities of the fundamental properties between different catalyst types. This combination of different catalyst types together with different catalyst aspects hopefully leads to in-depth conceptual understanding of the topic of catalysis.

In order to reach this full conceptual understanding of the material, the jigsaw method was adopted within the explorative module. The jigsaw method is a cooperative learning technique that reduces racial conflict among school children, promotes better learning, improves student motivation, and increases enjoyment of the learning experience (Aronson et al., 1978). Each jigsaw group was commissioned to investigate several possible materials, of either homogeneous-, heterogeneous or biological nature. The common property amongst these materials being they all catalyze the decomposition of hydrogen peroxide (H_2O_2). Dividing their jigsaw group over four possible materials, students performed experiments using either catalase from potatoes as biocatalyst; manganese(IV)dioxide (MnO_2) as heterogeneous catalyst; and iron(III)- (Fe^{3+} (aq)) or iodide-ions (I^- (aq)) as homogeneous catalysts. With the help of additional sources on their subject, students answer questions specific to their chosen catalyst and perform experiments with this particular catalyst and become an expert in their type of catalyst. Then, in the final part of the module, the jigsaw group is brought back together and every student is able to share their expert knowledge with the rest of the group. The jigsaw group is asked to complement an advisory report, of which the categories were inspired from Toulmin his model of argumentation as depicted in Figure 3, to conclude which catalyst works best for use in a large-scale plant (Chander et al., 2017; Toulmin, 1958). Students have to discuss which aspect is given priority above others whilst learning about the different types of catalysts through the knowledge of their jigsaw group partners.

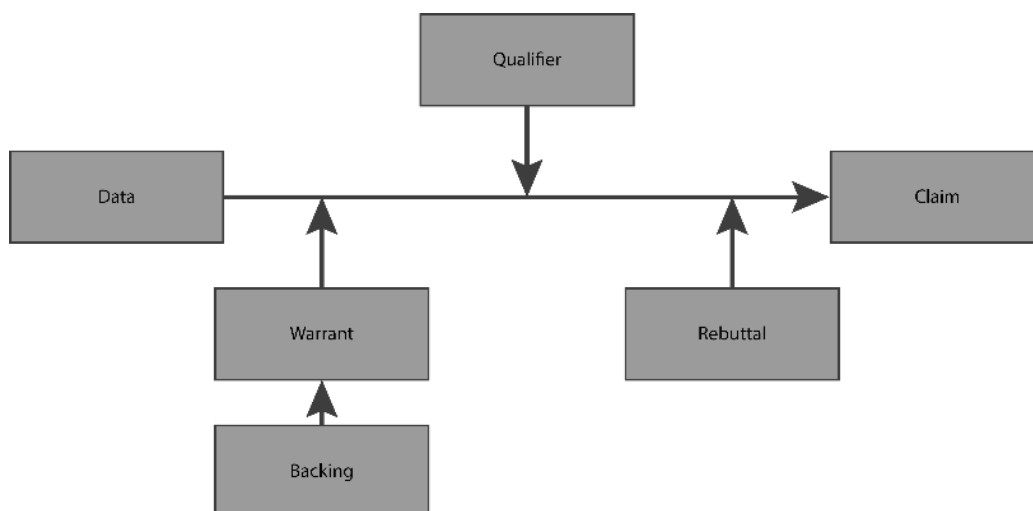


Figure 3: Toulmin's model of argumentation. An 'argument' consists in his analysis of a 'claim' (or conclusion, opinion or statement) based on factual evidence, 'data'. 'Warrants' (or principles or beliefs) are used to connect 'data' and 'claim' in a sensible way. 'Backings' can be used to corroborate 'warrants'. A further distinction is made with the 'rebuttal', in which refutation is given to possible criticism. In 'qualifiers', the limits of the validity of the conclusion are indicated. According to the model, 'data' and 'warrants' are part of every argument. Unlike 'backing', 'qualifier' and 'rebuttal', which do not always have to contribute to an argument.

The requirement for an experiment in a natural classroom setting was mainly conceived to mimic the trial and error approach of catalyst research (Li et al., 2020). Students gave substance to this requirement, by empirically determining the activation energy of hydrogen peroxide decomposition using different catalysts. Normally, such a determination would call for the measurement of the rate constant k at different temperatures. Running reactions at different temperatures, however, can be problematic not only because it is time consuming, but also because it is almost impossible to control for variations in temperature. Luckily, it is possible to study kinetics by using temperature versus time data, if the conditions of the process can be assumed adiabatic. With this in mind, Sweeney et al. (2014) published a time efficient experiment in which students use the exothermic nature of the hydrogen peroxide decomposition to determine activation energy over just one catalyzed reaction using only a thermometer (Sweeney et al., 2014).

As a measure to supplement the experiment described by Sweeney et al. (2014), the experiments were expanded for the use of heterogeneous and biocatalysts. In the resulting design, students started with a pilot experiment in which they performed the reaction in an Erlenmeyer flask without isolation. This way, they could visually observe the reaction after addition of the catalyst. When the reaction came to an end, students were asked to add some more hydrogen peroxide to observe that the catalyst is still present after the reaction. After the pilot experiment, students build their own calorimeter. In the reactor, hydrogen peroxide was combined with one of the four beforementioned catalysts. Temperature data was collected at 10 s time intervals until the reaction was clearly over. Students were guided to gather two full data sets if possible within the available time. Each data set led to the construction of two graphs, the first depicting temperature ($^{\circ}\text{C}$) versus time (s), as seen in Figure 4. By approximating the slope of the curve using Function 1, the value of k' can be determined using Function 2 leading to the second graph, the Arrhenius plot.

Function 1

$$(\text{slope})_T = \frac{\Delta \text{temperature}}{\Delta \text{time}} = \frac{T_2 - T_1}{t_2 - t_1}$$

Function 2

$$k'(T) = (\text{slope})_T \cdot \frac{T_{\text{final}} - T_{\text{initial}}}{T_{\text{final}} - T}$$

Testing the design

Shown in Figure 4 is the temperature increase over time using the four different catalysts. As seen in this graph, the temperature normally rises to about 60-70 °C after addition of the catalyst. When using catalase, however, this was found to not be the case as the temperature seems to halt at around 30 °C. A possible explanation for this could be the self-inhibition of the catalysis reaction by H_2O_2 , oxidative damage of the catalase by H_2O_2 (Lewis et al., 2009) or denaturation of the enzyme, probably due to altering pH-levels. This factor of instability led to the fact that setting up the Arrhenius plot using catalase was not possible, therefore no conclusion can be made upon the value of the activation energy of hydrogen peroxide decomposition using catalase as catalyst. This was different for the remaining catalysts. Significant temperature increases led to construction of the Arrhenius plot, as seen in Figure 4.

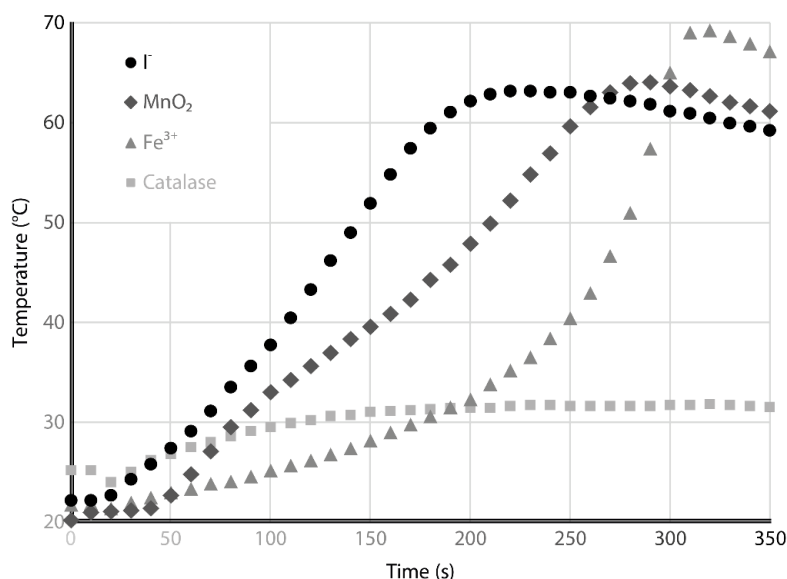


Figure 4: Results of testing the experimental methodology. As can be seen in the graph, the use of MnO_2 results in a somewhat random pathway. Normally temperatures of around 60-70 °C are reached during an experiment, although Catalase deviates from this.

The slope of the Arrhenius plot, as depicted in Figure 5, is used to determine the value of the Activation energy. In order to gain a reliable linear plot, the temperature increase should behave as an exponential S-curve. Both homogeneous catalysts comply to this, but that was not the case with the heterogeneous catalyst MnO_2 . This catalyst shows a fairly random pathway with respect to the increase in temperature, which can probably be explained by film diffusion and adsorption effects only applicable to heterogeneous catalysts. While these effects seem small at first, the real consequence becomes clear in the Arrhenius plot where MnO_2 forms a rather non-linear line with a correlation factor of only 0.5110, questioning the reliability of the measurement.

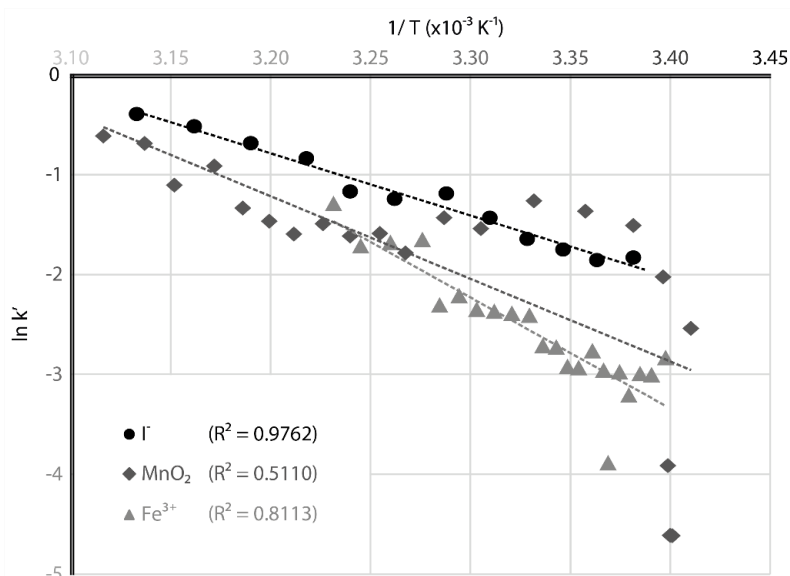


Figure 5: Resulting Arrhenius plots of testing the experimental methodology. Correlation factors of both homogeneous catalysts were valued fairly high. The random pathway of MnO₂ obtained in Figure 3 resulted in a non-linear Arrhenius plot, with a low correlation factor. Furthermore, since the test-runs of Catalase did not show any increase in temperature, it was not possible to construct an accompanying Arrhenius plot.

Seen in Table 4 are the activation energies determined from testing the design.

Catalyst	Type	Activation energy (kJ·mol ⁻¹)
Catalase	Biocatalyst	Not applicable
MnO ₂	Heterogeneous	68.6
Fe ³⁺	Homogeneous	92.0
I ⁻	Homogeneous	51.6

Table 4: Empirically determined values of activation energies of the decomposition of hydrogen peroxide using different types of catalysts.

Empirical methodology

The new prototypical module was tested in a natural classroom setting. In June 2021, at 'Openbaar Lyceum De Amersfoortse Berg', 83 eleventh grade students divided over three classes received a total of three lessons of around 45 minutes each in which the prototypical module has been carried out, the first of three lessons was designed as a pre-lab session in which the jigsaw groups answered questions regarding safety and availability of their catalyst. Experiments were carried out in expert groups during the second lesson. Processing of the experimental results was done during the third and final lesson. After processing the results, the jigsaw group uses the rest of the third lesson to compare results and write down their advisory report.

In one of the three classes, the experiment was performed a week earlier in relation to the other classes. This gave the opportunity to use the first class as a pilot group after which several improvements could be implemented to the design. Improvements led to a design that was more time-efficient, as students seemed to struggle with performing the full experiment within the available time as well as processing the data using Excel. Therefore, the pilot experiment was replaced by a demonstration by the instructor and students were handed an Excel document programmed to perform the calculations and construct the necessary graphs for them. These new implementations seemed to enable the students from the other two classes to perform the experiments in time. It turned out to be achievable for the pilot group to finish the initial design with one additional lesson. And since there were no adjustments on the didactical approach of the design between the three different groups, it was decided to include the results of the pilot group within further data processing.

Data collection

For the data collection, several sources of data were used. The main source of data were the qualitative data from the advisory reports written by each jigsaw group. The advisory reports stimulated students to form a statement as to which catalyst was the best fit for a large scale industrial process. Alongside the claim, students were asked to substantiate their position by adding arguments backed up by data they had found/collected earlier in the design, either empirically or theoretically. These arguments were collected as a single student statement. Further processing steps, such as coding, are explained in the next subsection and in Table 6. Alongside the advisory reports, given answers to questions in the discussion section of the module were also collected as data. These answers were used to extract empirical data from each jigsaw group, forming the empirical results section. Besides this, the results could also be used in a few select cases with the purpose to complement incomplete students statements. For example, if a jigsaw group failed to mention which specific catalyst they claimed to be the best fit, it is not possible to form a student statement out of their advisory report. However, if they mention observations such as “this catalyst had the lowest activation energy”, then the chosen catalyst can be derived from the given answers in the discussion section of the design (Appendix A).

As a matter of enhancing data triangulation over the qualitative data written in the reports, students were asked a few questions while handing in their final advice. During this very brief interview, which took only two minutes at most, students were given the opportunity to further substantiate their findings. The interview was semi-structured, in the sense that an interview protocol was at hand, however, questions were mainly directed to statements that raised questions with the teacher. For example when it was clear that an advise was based on misconceptions or when certain indistinct statements were written down. Some examples of interview questions are seen in Table 5.

Some exemplary questions from the interview protocol
The advise that you have written states that catalyst X is the preferred catalyst, which other catalysts have you investigated and why is this the preferred one?
Certain aspects are not mentioned in the advice. Have you thought about these aspects? What was the reason to not incorporate them into the advice?
The first aspect that was mentioned was aspect X. Does this mean that this is the most important argument in favor of the catalyst? And why do you think this aspect is the most important?
How sure are you of these test results? What can you state about the reliability of the experiment?
Are there any conditions that have to be taken into account when applying this catalyst at industrial scale?

Table 5: Exemplary questions from the interview protocol.

Data processing

Among 83 students that participated in the study, 23 jigsaw groups (9 among the pilot class and 14 among the remaining classes) managed to hand in their final advisory report (some jigsaw groups had to be merged into each other due to absent students). All results were initially collected in Dutch and translated to English to enhance readability. Due to the exemplary nature of the study, there was no seconds assessor, however, the findings and main conclusions have been discussed several times with the supervisor. Some advisory reports were filtered out due to unusable answers that had nothing to do with the study, resulting in a data pool from 21 jigsaw groups after selection (8 among the pilot class and 13 among the remaining classes). To illustrate some of the collected data from the advisory reports, two advisory reports are showcased in Table 6. Among this data pool, one thing stood out in particular. It was clear that a lot of jigsaw groups had left their advisory reports incomplete. Sometimes filling in only one argument or not fully constructing their arguments by leaving out the according backing, qualifiers or rebuttals necessary for a complete argumentation according to Toulmin his model. Rejecting all incomplete advisory reports for the study would leave a very inadequate number of reports for the investigation, which is not at all desirable. Therefore, during further analyzation of the results, all argument groups, combined with accompanying answers from the interview, were collected as an individual student statement. The full group of student statements were then further analyzed. This way, all incomplete advisory reports could remain part of the study.

Advisory report	Student result
Claim The goal of this study was writing an advisory report about which catalyst is suitable in the decomposition of hydrogen peroxide. Based on the performed research, we advise de following catalyst(s):	
	<input type="checkbox"/> Catalase A, C, D: <input checked="" type="checkbox"/> Fe^{3+} <input type="checkbox"/> MnO_2 B: <input checked="" type="checkbox"/> I^- <input type="checkbox"/> None of the above <input type="checkbox"/> Otherwise
Data Our first argument that reinforces this advice is based on the following fact:	
	A: The activation energy is lower when using Fe^{3+} as a catalyst. B: The activation energy. C: Little energy necessary. D: Fe^{3+} has the highest activation energy.
Argument group 1	Warrant This data supports our conclusion as follows:
	A: 103.190,449 $J \cdot mol^{-1}$ (the experimental activation energy of Fe^{3+} , ed.) is lower than 290.025 $J \cdot mol^{-1}$ (the experimental activation energy of catalase, ed.). B: I^- as catalyst decreases the activation energy the most. C: More sustainable because the activation energy was 3.132 $J \cdot mol^{-1}$ in relation to 13.987 $J \cdot mol^{-1}$ (MnO_2) and 66.487 $J \cdot mol^{-1}$ (I^-). D: The activation energy of Fe^{3+} is 94.477 $J \cdot mol^{-1}$.
	Backing The following (untested) assumption has been taken into account:
	A: The catalyst has caused the activation energy to drop. B: That working with this catalyst is not too difficult in terms of safety. D: Some different measures.
	Qualifier We can state with certainty that this substantiation is valid, because:
	A: The experiment was performed twice. C: We cannot tell for sure, because there was no duplo measurement. D: We measured both experiments twice.
Data Our second argument that reinforces this advice is based on the following fact:	
Argument group 2	A: Easy availability of Fe^{3+} . B: The price of the catalyst.
	Warrant This data supports our conclusion as follows:
	A: Easy to mine. B: Amongst the three tested catalysts, I^- is available for the lowest price per kilogram.
Backing The following (untested) assumption has been taken into account:	
	A: The mines remain open.
Data Our third argument that reinforces this advice is based on the following fact:	
Argument group 3	A: Fe^{3+} is not toxic in small amounts. B: The stability of the catalyst.
	Warrant This data supports our conclusion as follows:
	A: Data from Binas (science reference book, ed.). B: The reaction process remained unviolent and was continuous.
	Backing The following (untested) assumption has been taken into account:
	A: Accurate information in Binas.
Qualifier We can state with certainty that this substantiation is valid, because:	
	A: The Binas book is scientifically recognized.
Rebuttal Some preconditions that must be taken into account in this advice are:	
	A: This research should be repeated. B: Safety and recovery.

Table 6: Collected advisory reports of jigsaw groups A and B in complete form. Both can be regarded as good practice: jigsaw group A using Toolmin's guidelines to full extend to explain an argument and jigsaw group B prioritizing aspects as intended. Partial advisory reports of jigsaw groups C and D, showing only argument group 1.

To illustrate the process of extracting student statements which in turn needed to be coded, two fragments of the advisory report of two different jigsaw groups are shown in Table 6. Placing the raw data of jigsaw group C back to back would result in the following student statement: “Little energy necessary. - More sustainable because the activation energy was $3.132 \text{ J}\cdot\text{mol}^{-1}$ in relation to $1.3987 \text{ J}\cdot\text{mol}^{-1}$ (MnO_2) and $66.487 \text{ J}\cdot\text{mol}^{-1}$ (I^-). - We cannot tell for sure, because there was no duplo measurement.” Combining these sentences led to the following statement: “ Fe^{3+} is the most sustainable catalyst, because the activation energy was $3.132 \text{ J}\cdot\text{mol}^{-1}$ in relation to 13.982 (MnO_2) and 66.487 (I^-).” This statement relies heavily on the aspect of activity and was given code A, since the words ‘most sustainable catalyst’, in combination with the fact that $3.132 \text{ J}\cdot\text{mol}^{-1}$ is stated as the lowest value of activation energy, pleads in favor of the chosen catalyst.

Contrary to this, is the student statement of jigsaw group D. Placing the raw data of jigsaw group D back to back would result in the following student statement: “ Fe^{3+} has the highest activation energy. - The activation energy of Fe^{3+} is $94.477 \text{ J}\cdot\text{mol}^{-1}$. - Some different measures. - We measured both experiments twice.” Combining these sentences led to the following statement: “ Fe^{3+} is the advised catalyst. Because after measuring twice, the activation energy was determined to be highest when using Fe^{3+} , being $94.477 \text{ J}\cdot\text{mol}^{-1}$.” This statement also relies heavily on the aspect of activity. But distinguishes itself from code A due to the fact that $94.477 \text{ J}\cdot\text{mol}^{-1}$ was empirically determined as the highest activation energy instead of the lowest, therefore receiving a different code, code C. Shown in Table 7 is the full list of codes given.

Aspect	Code	Description
Activity	A	Pleading in favor for the advised catalyst by mentioning the low activation energy.
	B	Pleading in favor of advised catalyst by mentioning the high activation energy.
	C	Pleading in favor of the advised catalyst by mentioning the final level of temperature of the reaction process.
	D	Pleading in favor or against a catalyst by mentioning temperature increase over time
	E	Pleading against one of the catalysts to invigorate other statements.
Availability	F	Pleading in favor for the advised catalyst by mentioning its availability as advantage.
	G	Pleading in favor for the advised catalyst by mentioning its low price as advantage.
	H	Pleading in favor of advised catalyst by mentioning its availability as well as the low price as an advantage.
Safety	I	Pleading in favor for the advised catalyst by mentioning the lack of necessary safety requirements as an advantage.
	J	Pleading in favor for the advised catalyst by mentioning high safety risks of other catalysts as disadvantage.
	K	Pleading in favor for the advised catalyst, while still mentioning a relevant disadvantage.
Stability	L	Pleading against one of the catalysts by mentioning a lack of stability as disadvantage.
	M	Pleading in favor for the advised catalyst by mentioning a lack of stability from another catalyst as a disadvantage.
	N	Pleading in favor of advised catalyst by mentioning its stability as an advantage.
Recovery	O	Pleading in favor for the advised catalyst by mentioning its recovery path as an advantage.
	P	Pleading in favor for the advised catalyst by mentioning that it is still present after the process.
	Q	Pleading in favor of advised catalyst by mentioning that recovery is not necessary.

Table 7: Coding scheme used for coding the individual student statements extracted from the advisory reports. This coding scheme is the result of an open coding process.

Besides the theory discussed in these student statements. The order in which they are given can be used to set up a sort of ‘weighted average’ between the five different aspects of catalysis, which can be used to conclude which data students found more valid for their advisory report. For this weighted average, each argument has been given a score from one to three. Three points were assigned to each aspect that was given as first argument, two points for aspects prioritized at second place and one point for aspects that have been given as third argument.

Results

This result section contains the student outcomes after testing the design in natural classroom setting. These students outcomes are twofold. At first, empirical results, extracted from the questions in the discussion section of the explorative teaching module, are stated. Secondly, student statements, extracted from the advisory reports and accompanying interview, are shown.

Empirical results of testing the design in a natural classroom setting

Jigsaw groups could choose two or three possible catalysts among a pool of four catalysts, and in order for a weighted average to be determined, it is necessary to gain an indication whether all four catalysts have been studied evenly. Manganese(IV)oxide has been investigated by 16 of 21 jigsaw groups; catalase by 14 of 21; iodide by 15 of 21 and iron(III) by 6 of 21 groups. Amongst the advisory reports, manganese(IV)oxide was chosen 5 times; catalase 4 times; iodide 2 times; iron(III) 5 times and other possibilities 3 times (all three occasions involved a combination of multiple given catalysts). The experimental values of activation energy were not always provided by students, but the collected results vary sizably. Experimental results on manganese(IV)oxide averaged out on $103 \text{ kJ}\cdot\text{mol}^{-1}$ but varied from $14 \text{ kJ}\cdot\text{mol}^{-1}$ to $151 \text{ kJ}\cdot\text{mol}^{-1}$ to some negative values which are impossible; experimental results on catalase averaged out on $150 \text{ kJ}\cdot\text{mol}^{-1}$ but varied from $57 \text{ kJ}\cdot\text{mol}^{-1}$ to $411 \text{ kJ}\cdot\text{mol}^{-1}$ to no result measured; experimental results on iodide averaged out on $64 \text{ kJ}\cdot\text{mol}^{-1}$, varying from $40 \text{ kJ}\cdot\text{mol}^{-1}$ to $98 \text{ kJ}\cdot\text{mol}^{-1}$ and experimental results on iron(III) averaged out on $81 \text{ kJ}\cdot\text{mol}^{-1}$, varying from $3 \text{ kJ}\cdot\text{mol}^{-1}$ to $107 \text{ kJ}\cdot\text{mol}^{-1}$.

Student statements extracted from the advisory reports and accompanying interview

According to the participants, catalyst activity is seen as the leading argument in the advisory reports, scoring 58 points. Followed by catalyst availability, 16 points; -safety, 15 points; -stability, 11 points and lastly the aspect of catalyst recovery with 3 points. In this subsection, student statements regarding each of the five aspects are isolated and categorized in tables. Every table is sorted by code, followed by the accompanying advised catalyst. This shows the wide variety amongst collected advices. At last, each statement is checked for possible misconceptions. For example: Code 'A' statements pleading in favor for the advised catalyst by mentioning the low activation energy are mostly always correct since students applied the concept of activation energy in the right way, unlike code 'B' statements where they mistakenly mentioned the high value of the activation energy as an advantage. A code 'A' statement such as "*the lower the activation energy is, the better. Therefore catalase works best*" was considered 'gray area', because although students are correct about their claim, the empirical activation energy of catalase leading to this claim is not reliable as stated before.

Shown in Table 8 are the student statements regarding catalyst activity. Statements are categorized as follows: A) pleading in favor for the advised catalyst by mentioning the low activation energy; B) pleading in favor of advised catalyst by mentioning the high activation energy; C) pleading in favor of the advised catalyst by mentioning the final level of temperature of the reaction process; D) pleading in favor or against a catalyst by mentioning temperature increase over time; E) pleading against one of the catalysts to invigorate other statements. Each student statement containing code B or C is stated to be incorrect. Respectively due to the fact that students either incorrectly label a higher value of activation energy as a positive characteristic or incorrectly link the value of the activation energy to the increase in temperature. Regarding code D: some students stated that the activation energy resulted in a quick temperature increase, these statements are deemed partly correct. This is because students link the activation energy incorrectly to the rise in temperature, however, a good catalyst would ultimately result in a high turnover rate which in the end results in an increase of temperature. The last thing to take in mind regarding these statements is the fact that some students advised catalase to be the best catalyst due to its low activation energy (Code A - catalase). This is remarkable, because in the used environment, the stability of catalase is too insufficient to even complete the reaction.

Code	Advise	Students statements regarding catalyst activity	Correct
A	I ⁻	I ⁻ decreases the activation energy the most.	+
		The lower the activation energy, the better. And according to our research, I ⁻ decreases the activation energy to a value of 56.746 J·mol ⁻¹	+
		I ⁻ provides the lowest activation energy.	+
		When investigating catalysts, activation energy is the main focus. During the experiment, something weird happened during the determination of the activation energy of MnO ₂ leading to -34.278 J·mol ⁻¹ . Neglecting that, the activation energy is lowest when using I ⁻ , being 40.433 J·mol ⁻¹ .	+
	Catalase	The lower the activation energy is, the better. Therefore catalase works best.	±
		The activation energy is lowest in case of catalase, therefore catalase is most suitable for use in mass production.	±
		Activation energy of catalase is low, but not the lowest.	+
	Fe ³⁺	Fe ³⁺ is the most sustainable catalyst, because the activation energy was 3.132 J·mol ⁻¹ in relation to 13982 (MnO ₂) and 66487 (I ⁻).	+
		Due to the activation energy of Fe ³⁺ , Fe ³⁺ decreases the activation energy the most ,hydrogen peroxide is converted quickly.	+
		The activation energy is lower when using Fe ³⁺ as a catalyst, 103.190,449 J·mol ⁻¹ . In relation to 290.025 J·mol ⁻¹ for catalase.	+
		The activation energy was lowest with Fe ³⁺ , and therefore less energy is required for the reaction to take place.	+
	MnO ₂	Activation energy of MnO ₂ is low.	+
B	Catalase	Catalase has a quick activation energy of about 56.000 J·mol ⁻¹ and therefore accelerates the process well. MnO ₂ had less activation energy. This could be concluded from the experimental data we gained, there were, however, almost no reaction symptoms observable with catalase as catalyst.	-
		Fe ³⁺	Fe ³⁺ is the advised catalyst. Because after measuring twice, the activation energy was determined to be highest when using Fe ³⁺ , being 94.477 J·mol ⁻¹ .
	MnO ₂	MnO ₂ had the highest activation energy, and is therefore the best. MnO ₂ is the best catalyst because it has the biggest activation energy.	-
C	Catalase	Using catalase leads to a higher temperature increase.	-
	MnO ₂	MnO ₂ is a slightly good catalyst, but not the best. Because we heard other catalysts reached higher temperatures, but we did not measure those catalysts.	-
D	Fe ³⁺	The temperature increases quickest with Fe ³⁺ , so that one is the best.	±
		Fe ³⁺ works really fast. This was observed by a rapid rise in temperature.	±
	MnO ₂	MnO ₂ is slow, so therefore we would advise against it.	±
E	I ⁻ / Fe ³⁺	The difference in temperature increases heavily really quick when using MnO ₂ .	±
		The measured activation energy of catalase was invalid. But I ⁻ was determined at 40.017 J·mol ⁻¹ and Fe ³⁺ was determined at 107.410 J·mol ⁻¹ .	+

Table 8: Student statements regarding catalyst activity. Each correct statement is marked with '+'; while inaccurate statements are marked with '-' and statements which could be considered 'gray area' are marked with '±'.

Shown in Table 9 are the student statements regarding catalyst availability. Statements are categorized as follows: F) pleading in favor for the advised catalyst by mentioning its availability as advantage; G) pleading in favor for the advised catalyst by mentioning its low price as advantage; H) pleading in favor of advised catalyst by mentioning its availability as well as the low price as an advantage. Most statements are marked as correct, leaving two exceptions. I⁻ is not the cheapest catalyst and Fe³⁺ cannot be mined independently.

Code	Advise	Students statements regarding catalyst availability	Correct
F	I ⁻	I ⁻ is well available.	+
	Catalase	Potatoes are available anywhere, so it is well/easily obtainable.	+
	Fe ³⁺	The reaction process can take place more often, because Fe ³⁺ is widely available. Fe ³⁺ is easily obtained in mines.	±
G	I ⁻	I ⁻ has the lowest price of the three tested catalysts.	-
	Catalase	Since it comes from potatoes, which are very cheap. Catalase is the best buy.	+
		1 kilogram of potatoes is € 1,69. That is cheap.	+
Fe ³⁺	Fe ³⁺ is not incredibly expensive, so it is an achievable catalyst economically speaking.	+	
H	Catalase	Potatoes are super cheap and easily obtainable.	+

Table 9: Student statements regarding availability. Each correct statement is marked with '+'; while inaccurate statements are marked with '-' and statements which could be considered 'gray area' are marked with '±'.

Shown in Table 10 are the student statements regarding catalyst safety. Statements are categorized as follows: I) pleading in favor for the advised catalyst by mentioning the lack of necessary safety requirements as an advantage; J) pleading in favor for the advised catalyst by mentioning high safety risks of other catalysts as disadvantage; K) pleading in favor for the advised catalyst, while still mentioning a relevant disadvantage. Only one statement was found to be incorrect, being the statement with code J. This statement mentions that I^- is difficult to use because it is toxic to the touch. However, in large scale industrial plants, this will not be much of an issue.

Code	Advise	Students statements regarding catalyst safety	Correct
I	Catalase	Potatoes come with the least safety precautions. So it is safe to use.	+
		Catalase is found in grated potatoes among other things, and since there are barely any safety risks involved it can be said that catalase is a safe catalyst.	+
		Potatoes are quite safe.	+
	Fe^{3+}	Fe^{3+} is not harmful in small amounts, and also not harmful in water.	+
		In small amounts, Fe^{3+} is not really harmful.	+
J	Catalase	Potatoes are safe, <i>unlike I^- which is toxic if touched and therefore difficult to use.</i>	-
K	MnO_2	According to safety precautions, MnO_2 can be dangerous (it was advised however, ed.)	+

Table 10: Student statements regarding safety. Each correct statement is marked with '+'; while inaccurate statements are marked with '-'.

Shown in Table 11 are the student statements regarding catalyst stability. Statements are categorized as follows: L) pleading against one of the catalysts by mentioning a lack of stability as disadvantage; M) pleading in favor for the advised catalyst by mentioning a lack of stability from another catalyst as a disadvantage; N) pleading in favor of advised catalyst by mentioning its stability as an advantage. The statements bearing codes M and N were considered to be 'gray area', since these statements could potentially be true, but the design did not embed any sufficient warrants to back this statement to actual theory.

Code	Advise	Students statements regarding catalyst stability	Correct
L	Fe^{3+}	According to measurements, catalase does not work in the environment used in this experiment.	+
		MnO_2	The temperature did not increase, so catalase did not work.
	Other	Potato did not work and therefore MnO_2 was better.	+
		Potato cannot be used in industry because is not functioning, the temperature remains a flat line which indicates a flat course of events in the process. The rest of the catalysts did provide the expected graphs.	+
M	I^-	I^- is most stable, because Fe^{3+} is less stable.	±
N	Fe^{3+}	Fe^{3+} was stable, because the reaction process remained unviolent and was continuous.	±

Table 11: Student statements regarding stability. Each correct statement is marked with '+'; while statements which could be considered 'gray area' are marked with '±'.

Shown in Table 12 are the student statements regarding catalyst recovery. Statements are categorized as follows: O) pleading in favor for the advised catalyst by mentioning its recovery path as an advantage; P) pleading in favor for the advised catalyst by mentioning that it is still present after the process; Q) pleading in favor of advised catalyst by mentioning that recovery is not necessary. The statements bearing codes P and Q were considered to be inaccurate. Respectively, since being a product of the reaction as well as a substrate does not mean that it is easy to replenish and since using grated potatoes lead to a suspension which ultimately would need to be filtered or sieved in order to remove the catalyst from the reaction mixture.

Code	Advise	Students statements regarding catalyst recovery	Correct
O	MnO_2	MnO_2 is advised, because it is easy to replenish. This is due to it being a heterogeneous catalyst so therefore you can just get it back using a filter.	+
P	Fe^{3+}	Fe^{3+} is advised, because it is a reaction product. Therefore it is easy to replenish.	-
Q	Catalase	Potatoes do not need to be filtered.	-

Table 12: Student statements regarding recovery. Each correct statement is marked with '+'; while inaccurate statements are marked with '-'.

Discussion

Now that the gathered results are known, the conceptual learning outcomes that have become visible through the set of student statements can be compared with the intended learning outcomes. And since the five catalytic aspects that are comprised in the exploratory teaching module can be seen as representations of scientific literacy in relation to catalysis, implications can be made if students have gathered scientific literacy about the fundamental concepts of different types of catalysts, according to whether or not the achieved learning outcomes match the intended learning outcomes. Besides this comparison, a reflection is given on the reliability of empirical data that was harvested after applying the described experimental methods.

Achieved learning outcomes on the aspect of catalyst activity

Regarding the statements about catalyst activity, students statements were mostly set up as intended. It is seen that 14 out of 21 jigsaw groups made a statement in which they, as was intended by the design, pleaded for a catalyst stating that it had a low activation energy (code A or E statement), against 4 jigsaw groups that made a statement in which they pleaded for a catalyst stating that it had a high activation energy (code B statement). These four jigsaw groups show a fundamental misconception about catalysis, misunderstanding that for a more active catalyst, the activation energy of the catalyzed reaction should be lower and not higher.

Furthermore, in reviewing student statements concerning the activity of the catalyst, 4 jigsaw groups made statements concerning concepts outside the intended conceptual framework. These jigsaw groups connected the activity of a catalyst to time related observation, such as how quick the temperature raised (code D statement). Although it is possible to express catalyst activity in relation to time, such is done when for example determining the turnover frequency of a catalyst, this concept was not mentioned in the design. At last, 2 jigsaw groups had linked the activation levels of a catalyst to the final level of temperature reached. These statements are incorrect, since the resulting enthalpy of the reaction is thermodynamically independent on the height of the activation, and therefore are not affected by the used catalyst.

Achieved learning outcomes on the aspect of catalyst availability

As for the intended learning outcomes on catalyst availability, this aspect was mostly implemented into the design so students could search and compare certain chemical properties of the different types of catalysts. In this case, the design led students to investigate the selling price for their chosen catalyst. The height of the price can often be brought into connection with the availability of the catalyst, and makes for an easy comparison amongst different catalysts. Pricing of MnO_2 and iron(III)salts are mostly of around € 50-60 per kg, while iodide containing salts are a bit more expensive at around € 300-400 per kg. At the other end of the spectrum is catalase, which can easily be extracted and purified from multiple sources of vegetables. 9 out of 21 jigsaw groups mentioned the availability and/or the low price of the catalyst as a benefit for using this specific catalyst (code F, G or H statement). However, some statements are not giving any data or warrants to their claim, and all jigsaw groups failed to actually compare different catalyst availabilities to each other. Therefore it can be said that the intended learning outcome on this specific aspect has not been reached.

Achieved learning outcomes on the aspect of catalyst safety

In term of safety, students could have found several safety issues regarding the different types of catalysts. MnO_2 , for example, may cause damage to organs through prolonged or repeated exposure and is also harmful if swallowed or if inhaled, according to its material safety data sheet. Even catalase, which seems very harmless at first when accounting for the fact that it is originated from potatoes, is suspected to cause allergy or asthma symptoms or breathing difficulties if inhaled. However, the chemical industry has lots of experience handling chemicals that are much more dangerous than the ones used in this experiment. Besides, the necessary amounts of these materials are also small-scale, since only catalytic amounts are necessary. The key concept of this aspect therefore is that safety precautions do not really influence this particular decision. Still, out of 21 jigsaw groups, 7 groups stated about safety, of which 2 groups about the fact that one of the materials was unsafe to use. The other 5 student statements, however, mostly mentions the fact that the advised catalyst is safe to use (in small amounts). This, together with the fact that most jigsaw groups did not prioritize catalyst safety as an important aspect in their decision making process, lead to the conclusion that the intended learning outcome on this specific aspect have been reached.

Achieved learning outcomes on the aspect of catalyst stability

In terms of stability, the key intention students should have brought up was the fact that catalase was instable as a catalyst. Out of 21 jigsaw groups, 6 groups stated about stability, of which 4 groups about the fact that catalase was unstable. Unfortunately, these jigsaw groups did not state the actual reason for this catalyst to be instable. Students were handed out appendices with accompanying information about enzyme stability in relation to temperature optima and pH-optima. The intended learning trajectory was that students deduced that the inactivity of catalase should have been caused by enzymatic denaturation, probably due to shifts in pH above temperature, since thermal inactivation of catalase does not logically occur in 20-40 degrees temperature range occurring (Anthon & Barrett, 2002; Eyster, n.d.). Further literature study revealed that the more probable cause for catalase inactivity could be the self-inhibition of the catalyzed reaction by H_2O_2 or oxidative damage of the catalase by H_2O_2 (Lewis et al., 2009). Regardless the actual reason for the catalase inactivity, it can be stated that students did not achieve to make any statements regarding why catalase would be instable and therefore the intended learning outcomes on this aspect do not match the actual learning outcomes of the students.

Achieved learning outcomes on the aspect of recovery

In terms of recovery, the key intention students should have brought up was the fact that a heterogeneous catalyst is much easier to remove from a reaction mixture compared to a homogeneous catalyst. Out of 21 jigsaw groups, 1 jigsaw group stated exactly the intended learning outcome. 2 other groups stated inaccurately that iron(III)-ions are easy to replenish due to it being a product of the reaction and that grated potatoes do not need to be filtered. Those statements are incorrect and the students who made these statements probably have not obtained the key concept of this aspect. It would, however, be bold to assume that this means that students did not achieve the intended learning outcomes, since this aspect was only mentioned in the advisory report by three jigsaw groups. That amount is a little too few to reliably make a statement on whether the total population in general did achieve the intended learning outcomes or not.

Reliability of the experimental method

In the attempt to combine three different types of catalysts in one experiment, one issue has risen that could affect the reliability of the experiment, being the observation that the implementation of different types of catalysts in the experiment complicates the correct determination of the activation energy. In general, valued activation energies empirically determined deviated strongly from known theoretical values. To the extent that iodide-catalyzed activation energy was empirically valued to $64 \text{ kJ}\cdot\text{mol}^{-1}$, while the theoretical value is determined at $56 \pm 3 \text{ kJ}\cdot\text{mol}^{-1}$ (Sweeney et al., 2014); with iron(III)-catalyzed decomposition the empirical value was averaged at $81 \text{ kJ}\cdot\text{mol}^{-1}$, while theory suggests a value of $35 \pm 2.5 \text{ kJ}\cdot\text{mol}^{-1}$ (Haber et al., 1934; Lin & Gurol, 1998); with the heterogeneous catalyzed reaction using MnO_2 the empirical value was averaged at $103 \text{ kJ}\cdot\text{mol}^{-1}$, even including some impossible negative values, while theory suggests a value of either $35 \pm 14 \text{ kJ}\cdot\text{mol}^{-1}$ (Zipp et al., 1998) or $41.3 \pm 3.5 \text{ kJ}\cdot\text{mol}^{-1}$ (Tatsuoka & Koga, 2013).

One cause for this rather large deviation in student results could be poor thermal insulation of the reactor. This may cause thermal leakage during the measurements, which has direct correspondence on the reliability of kinetic data from a thermometric curve (Tatsuoka & Koga, 2013). In this case, a poor insulation leads to a decreased slope of the thermometric curve, which at its turn causes the slope of the Arrhenius plot to increase leading to a higher determination of the activation energy. Another cause for the rather large deviation could be hidden in the way the data is processed. When reaching T_{final} , the use of Function 2 becomes too uncertain since the slope of the thermometric curve is approaching zero while $(T_{final} - T_{initial}) / (T_{final} - T)$ approaches infinity. It is due to this reason that some of the latter data points have to be excluded from further data processing. The chosen uncertainty interval, however, holds a direct impact on the final results. This particular thinking process was very difficult for the pilot group to comprehend, since the thought process of data processing got lost in detail from operating Excel, a program that the students seemed very unfamiliar with. In the template for the other classes, there could be a possibility that this data correction will not fit every single individual measurement as intended. At last, it is thought that the effects of film diffusion and adsorption of H_2O_2 play a bigger disadvantage when using a heterogeneous catalyst in this experimental method, since the obtained thermometric curve shows a deformation from the exponential S-curve observed when using homogeneous catalysts.

Conclusion

The reason for this empirical research concerning the subject of catalysis, was to investigate if a shift in the approach of Dutch secondary chemistry education would enable for a more coherent and true to nature chemistry curriculum. The remaining research question left to answer is:

“To what extent does the explorative teaching module, that combines the topics of homogeneous-, heterogeneous- and biocatalysis, enable students in secondary chemistry education to gain an in-depth conceptual understanding of the topic of catalysis?”

In order to come to a conclusion, a conceptual framework of catalysis was constructed and compared to the current curriculum in Dutch secondary chemistry education. In an attempt to reduce fragmentation in the conceptual framework, prototypical teaching material was designed in which students were introduced to a more true to nature view of the field of catalysis. This design was tested in a natural classroom setting.

Conclusion

Empirical determinations on activation energy varied widely and were not always consistent with values stated in the literature, though they led students to learn about the intended learning trajectory on five different aspects catalysis that represent scientific literacy on the domain of catalysis. Learning outcomes show that the achieved outcomes match the intended outcomes regarding just one of the five aspects, being catalyst safety. Unfortunately, however, the intended learning outcomes on the more extensive aspects of catalyst activity, availability, stability and recovery, were not met. The final conclusion is therefore that the designed prototypical teaching material does not enable students to gain an in-depth conceptual understanding of the domain of catalysis to the intended extend.

Limitations

With regards to the data processing of the student outcomes, the coding has been performed without a second coder. In addition, during testing of the prototypical module the researcher also took on the role of teacher. These two factors are highly unlikely, and may have influenced the results. It was, however, a deliberate choice, due to the prototypical nature of the teaching module. The design was tested only at ‘Openbaar Lyceum The Amersfoortse Berg’, upscaling the experiment may not lead to the same results. One of the main limitations of the prototypical teaching module was that the required data processing was too comprehensive for students. This kept them from coming to well-structured arguments within the available time of three lessons. An Excel template was added to the design in order to assist students to save time during this phase, but some necessary data corrections were difficult to generalize.

Recommendations

Although the prototypical lesson module may not lead to the intended learning outcomes in the available time. There are some recommendations that can be of interest in further research around this subject. The hypothesized misalignment between the chemical industry and the Dutch secondary chemistry curriculum is proven and a solution is required in order to bring back coherence between the curriculum and the industry. Therefore catalysis as central domain to enhance scientific literacy remains a probable solution to the curriculum misalignment. The prototypical teaching material enabled students to learn mainly about the aspect of catalyst activity, in particular the decreasing activation energy. This teaching module can therefore be used in classroom settings where learning about catalyst influence of activation is desirable. Some adjustments to the questions in the module are recommended, if the appeared misconceptions about ‘desired high activation energies’ and the ‘link between enthalpy and the value of the activation energy’ are to be evaded. The research aspect of combining the three different catalysts in which one group gets the assignment to write an advisory report could be tested in other teaching settings. Especially those with the ability to invest some more time or coaching, like a school research project. More time could enable students to delve more deeply into the subject and construct a better in-depth conceptual understanding of the different concepts related to the topic of catalysis.

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Appendix A

Exploratory teaching module (only available in Dutch):

Activeringsenergie bepalen van een gekatalyseerde ontledingsreactie.

Appendix B

Supplemental information (partly in Dutch):

Student outcomes from advisory reports and interviews.