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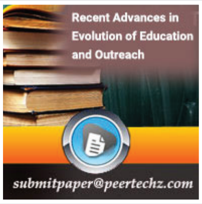

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Review Article

Fuels and Combustion: Definitions and Specifications for Didactic Transposition and Outreach Purposes

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Abstract

Starting from a literature inspection, an examination of the definitions of fuel and combustion found for educational and outreach purposes is conducted. In many textbooks, handbooks, slides, or websites that disseminate scientific topics, the definition of fuel (as a product) and of combustion (as a process) is skipped to give room to practical aspects such as classification and technical performances of fuels. Anyway, many unsatisfactory definitions of fuels and combustion are available, full of omissions, imprecisions, ambiguities, and even outright errors. The definition of combustion is often lacking and favours thermodynamic aspects while neglecting kinetic ones, as if it were disconnected from practice and phenomenal reality as it is understood today. The critical examination of the current teaching approach on fuels and combustion—with particular attention to the high school and university levels,— allows us to identify weaknesses and to propose new definitions more suitable to avoid grey areas of the lessons. It is also proposed to refine the definition of fuel by considering the inclusion of nuclear fuel and taking into account the humongous difference between a chemical decomposition and an atomic transmutation. With respect to metals as fuels, a comparison between burning and rusting of iron is also examined.

This is a fundamental topic of industrial chemistry, the teaching of which is based on a broad set of prerequisites and, in general, a good knowledge of basic chemistry. The subject of fuels and combustion is of interest to students in high schools (even if the educational path on fuels and energy can start with some rudiments from primary school) and universities, due to its obvious relationships with energy production systems, mobility, and everyday life. Fuels and related subjects can be an excellent theme to motivate students to study chemistry and applied chemistry. The importance of language and terminology in brain-based lesson planning is also discussed, considering the language as the barycentre of teaching/learning.

Introduction

Combustion is one of humanity's oldest and most essential chemical processes. Fuels are paramount commodities, and their demand in the markets is constantly growing. A range of commercial fuels is available to society to meet its energy needs. Precisely because of its close connection with energy production, the topic of fuels is treated at an outreach level by many websites and magazines, as well as by newspapers (both paper and online) and television news and programmes. For these reasons, delivering information on a core topic for survival and wellness requires knowledge to avoid the diffusion of inaccuracies or ambiguities that nurture the development of distortions and biases. With respect to the education sector, we are dealing with a fundamental topic of industrial chemistry, the teaching of which is based on a broad set of prerequisites and, in general, a good knowledge of basic chemistry. In general, the subject of fuels and combustion is of interest to students of high school (even if the educational path on fuels and energy can start with some rudiments from primary school) and university, due to its obvious relationships with everyday life, energetic policies, and environmental impact. For this reason, at least in certain types of high schools (focused on scientific and technical subjects), fuels and combustion can be an excellent theme to motivate students to study chemistry and applied chemistry.

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In many textbooks, handbooks, slides, or websites that disseminate (with the most different purposes) scientific topics, the definition of fuel (as a product) and of combustion (as a process) is often even skipped (as if it were a given) and the pivotal topic of fuels, combustion, and energy starts, after a very brief introduction, with the exposition of the *classification criteria* of fuels. This is really curious, but even worse is reading an incorrect, rough, or incomplete definition of what fuels and combustion are. This mess approach is harmful both at didactic and outreach levels, if you want a cultured society with people capable of discernment. Moreover, wide room is commonly left to the factors that need to be considered when choosing a fuel: its abundance in nature (primary fuels), its technical performances during burning, the technologies required to utilise the fuel, the implications for transportation and storage, and its impact upon the environment. All of this can be useful to the debate, but without a meaningful chemical foundation on which to build any discussion and evaluation, the goal of informing or educating cannot be achieved.

Scientific papers related to didactics on the topic under discussion mainly focus in analysis regarding details on single category of fuel rather than on energetic policies and related issues (roles of fuels in society, wars for fuels, environmental impact of fuels, etc.). At the border between the scientific and humanistic areas, Karen Pinkus' book entitled 'Fuel: A Speculative Dictionary' [1]—which is an idiosyncratic and speculative dictionary that explores both real and imagined fuels, historical and futuristic—deserves a citation. To introduce the literature analysis, specifically developed in the next paragraphs, according to the paper of Conrad and co-workers [2], 'All reactants can be fuels if they undergo exergonic reactions where the released energy is used to accomplish something tangible'. This attempt—like many others—to define what a fuel is in a chemical perspective put in evidence only the thermodynamic aspect of a combustion and, moreover, this definition fails to address the ambiguity existing between fuels and nuclear fuels, with the same name being used in many scientific papers and didactic sources improperly in the absence of detailed specifications. The first core question is: how many exergonic chemical transformations exist without any of the reactants being labelled as fuel? The second core question is: do we realise that combustion and nuclear transmutation are monstrously different processes, to the point that using the term *fuel* for both leads to confusion that is unacceptable from an educational perspective? The human brain widely uses generalisation to simplify the analysis of reality (easily losing details and nuances) and protect itself from tiring processing overload: for this reason, if concepts are expressed in a blurred way during lessons, students are sure to build inaccurate and confusing mental models of the information presented. The framework briefly examined to introduce to the topic of this paper highlights several weaknesses which, in the educational field, can hinder the development of a scientific mindset that is, on the one hand, the result of current scientific knowledge and, on the other, a driving force of critical thinking. Furthermore, chemistry is already difficult in itself; if it is taught by superficially conveying inaccuracies, incompleteness, and ambiguities, or by simplifying it to the point of distortion (leaving spaces for too wide margins of interpretation), we are fostering demotivation and building ignorance. Biases are very difficult to correct, and once a certain misconception has become embedded in the learner's cognitive system, it tends to take root and stabilise as if it were a certainty upon which new notions can be added and elaborated in a defective vicious circle. And this is where the learning of chemistry, and perhaps scientific disciplines in general, goes into crisis.

This speculative paper aims to shed light on this topic in order to construct an effective teaching model for the broad, complex, and fundamental subject of fuels and combustion. In particular, great attention is paid to the content examination of websites, because they are frequently consulted by school and university students, especially to find shortcuts that shorten study time by short-circuiting quality objectives to prioritise path speed.

Critical examination of the definition of fuel from a didactic perspective

The IUPAC (International Union of Pure and Applied Chemistry) Gold Book—Compendium of Chemical Terminology [3]—does not provide a definition of fuel but, rather, specialised entries for different fuel types, such as *fossil fuel*. It represents a black hole for the field of industrial chemistry and, in particular, for the didactics of fuels and related topics. The concept of fuel is only apparently simple and needs to be framed after a critical analysis of the most used definitions found in common reference sources.

On the Cambridge Dictionary (online version) one can read [4]: 'Fuel is a substance that is used to provide heat or power, usually by being burned'. EPA (Environmental Protection Agency by USA) considers a fuel to be a material used to produce heat or power by burning [5]. According to Encyclopedia.com [6] 'A fuel is any compound that has stored energy. This energy is captured in chemical bonds [...]. Energy is released during oxidation. The most common form of oxidation is the direct reaction of a fuel with oxygen through combustion'. In the chapter 4 (Fuels and Combustion) of the book entitled 'Engineering Chemistry II' [7] we read: 'Fuel is a combustible substance, containing carbon as a main constituent, which on proper burning gives large amount of heat, which can be used economically for domestic and industrial purpose'. On the Oxford Learner's Dictionaries (online version) one can read [8]: 'Fuel: any material that produces heat or power, usually when it is burnt'.

Many critical aspects emerge from these definitions and, in any case, none of them are suitable for educational use, particularly in high schools (especially those with a technical and scientific focus) and in universities (especially in scientific degree courses). The first question that arises spontaneously is: fuels are substances, materials, or compounds (these three words are cultural heritage of general and inorganic chemistry and do not need to be explained in this paper, because they are prerequisites for a chemistry-based lesson on fuels and combustion)? The sad reality is that we find ourselves considering definitions that are widely used by students but which are partial and some contain inaccuracies or even mistakes. *Substance* is a correct term, but the definitions using it fail to take into account the possibility of dealing with a fuel composed of a mixture of substances, such as gasoline or diesel. The term *material* is something of an evergreen term, particularly used in materials science and engineering chemistry when chemistry is not typically the focus of teaching. Moreover, the widespread definition 'A fuel is any compound that has stored energy' is incorrect. In fact, it should be highlighted that carbon (C) in coal, a common solid fuel, is not a compound. Furthermore, dihydrogen (H_2) is not a compound, yet it is a gaseous fuel. Therefore, although the definition provided by Encyclopedia.com [6] is wider than others it contains a significant mistake. In [7] carbon-free fuels (such as dihydrogen and ammonia) are excluded from the definition, so that it is reduced to describing a particular subcase, like the definition given in [6]. Food and Agriculture Organization of the United Nations [9] and ISO [10] defined fuel any energy carriers intended for energy conversion. This is a generic definition, correct in itself but unsuitable for use in an educational context (especially high schools and universities) as it lacks the essential specifications for understanding it at a chemical level. In higher education, we must resist oversimplification to pursue structured and nuanced learning, otherwise we risk the collapse of universal knowledge within a few decades. Keeping it complex that is resisting simplistic framings of educational content is an ethical duty of professors in higher education [11]. Reducing teaching practices to a flow of captivating images (in textbooks, handbooks, slides, etc.) at the expense of complex reasoning, dialectics, terminological appropriateness, and mathematical rigor is condemning students to become underdeveloped. From an outreach perspective, this is a basic, concise, and essential definition, and therefore suitable for use by a non-expert audience receiving neutral communication that is not intended to educate, nor to contribute to the development of skills, competences, or critical thinking (as didactic practices do). If we want to help people and students develop a broader and more in-depth vision of phenomena (building a scientific mindset), we need to communicate complexity without falling into oversimplifications that end up becoming confusing, distorting, and limiting. Clearly, concise definitions can be accepted from general dictionaries, but not from specialist dictionaries or other resources designed for educational use.

When preparing a lesson, it is necessary to remove ambiguities, approximations, and mistakes to avoid that blurry (widely interpretable) or really incorrect concepts enter students' knowledge archives. Clearly, everything has to be adapted and proportionate to the student's level of education; in this paper, the focus is on lessons for high school and university students.

The comprehensive definition of fuel is complex enough and made of many characterising chunks; a proposal of definition designed for didactic purposes is the following:

A fuel is a substance, or mixture of substances, that burns releasing energy in the form of heat or light. The process of combustion occurs through a redox chemical reaction involving, as reactants, the fuel and an oxidiser, commonly dioxygen. During combustion, fuel constituents undergo controllable chemical decomposition with the release of energy and by-products.

In an accurate lesson, intended for high school or university students, it is necessary to specify that the oxidiser most often encountered in the reality is dioxygen ($O_{2(g)}$, oxygen is the trivial name) but that other chemicals also work. Common oxidising agents are dioxygen, hydrogen peroxide, potassium permanganate, and the halogens. For example, burning dihydrogen ($H_{2(g)}$, a carbon-free fuel) with chlorine ($Cl_{2(g)}$) as an oxidiser also produces heat and a flame.

Digging deeper in the analysis, it can be observed that it is quite difficult to give a full definition of fuel independent of the concept of combustion; *product* and *process* are almost inseparable in the expository logic. This have to be explained in an accurate lesson on fuels and combustion.

It is also possible to formulate a lightly more concise definition of fuel—above all suitable for outreach purposes—leaving aside the more in-depth chemical details:

In essence, a fuel is an energy carrier capable of rapidly transforming, by way of a specific and controllable chemical process called combustion, potential energy stored in chemical bonds of the substances that constitute it into thermal or light energy to do work powering various systems.

According to ISO 13600 standard [12], an *energy carrier* is either a substance or a phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes.

The fact that a fuel must be able to be supplied as needed, and that this implies that combustion is a regulated and controllable process within specific devices, is remarkable in managing this topic:

- 'An important property of a useful fuel is that its energy can be stored to be released only when needed, and that the release is controlled in such a way that the energy can be harnessed to produce work' [13];
- 'An important property of a fuel is that the energy is released in a controlled manner and can be harnessed economically for domestic and industrial purposes' [14].

Nuclear fuel: expanded concept of fuel and its redefinition

As previously stated, fuel is a substance, or mixture of substances, that has potential energy stored in a chemical form. An exception to this right but limited definition is the so-called *nuclear fuel*, in which energy is stored in the nucleus of an atom (not in chemical bonds). The nuclear fuel cycle—defined as the series of processes through which materials pass in the course of electricity generation—is accepted as a subject in which graduating nuclear engineering students should be well-versed [15]. Furthermore, the topic of nuclear energy and

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related issues is also discussed at secondary school level. The energy is released when nuclei are:

- Joined, fusion process, or
- Split, fission process.

In this case, the term *fuel* is used improperly and it must also be underscored that nuclear fuel gets away from common fuel definitions found in textbooks, handbooks, or websites. These are clearly very different processes that have in common the release of *energy* and the formation of by-products (waste to manage). The epochal difference between the operating principles of classical and nuclear fuels is usually left implicit.

This is a *grey zone* of a lesson on fuels to monitor carefully in order to be able to distinguish between *different categories of phenomena and processes* related to energy production.

To overcome the ambiguity—capable of disorienting inattentive, listless or lazy students, or those lacking basic knowledge—a redefinition of *fuel* is needed. In this perspective, it is then necessary to re-examine the definition of fuel to widen it. The concept of fuel was in fact originally applied solely to those materials capable of releasing energy from breaking and reformation of chemical bonds. Only the outer shell electrons of the atoms are then involved in this chemical process. When the nuclear energy transition occurred (in the 1950s, moving from military applications to civil electricity generation), and took root in the world, the definition of fuel entered into crisis. For a long time, however, the old and well-established definition of fuel has also been applied—without aimed revision—to other sources of energy, such as that from nuclear phenomena. Suitable examples of definition to consider (at least as starting points, as hints) to meet this need are:

- ‘Fuel is any material that is burned or altered to obtain energy. Fuel releases its energy either through chemical means, such as combustion, or nuclear means, such as nuclear fission or nuclear fusion’ [13];
- ‘A fuel is a substance that produces useful energy either through combustion or through nuclear reaction’ [14];
- ‘Fuel: Any material substance that can be consumed to supply heat or power. Included are petroleum, coal, and natural gas (the fossil fuels), and other consumable materials, such as uranium, biomass, and hydrogen’ [16],
- ‘A fuel is a substance that releases usable energy either through: *1.* a nuclear reaction such as fission or fusion, *2.* an oxidation-reduction reaction with an oxidiser’ [17],
- ‘A fuel is anything that can release energy to perform work’ [2].

A general definition of fuel, designed for didactic purposes and also capable of including nuclear fuel, is the following:

A fuel is an energy carrier capable of rapidly transforming, by way of a specific and controllable physical or chemical process, potential energy into other forms of energy exploitable to do work capable of powering various systems.

Both fossil and nuclear fuels represent a concentrated, storable, and consumable source of energy.

Clearly, an expanded definition of fuel will necessarily be set with generic terms or through explicit citation of phenomena to be included within the revised definition. According to these definitions, the energy release can happen through redox (burning, chemical process) or nuclear (fission or fusion physical processes) transformations. Nuclear energy is due to transformations in the nucleus of atoms and the nature of the chemical elements (a radionuclide) is therefore not conserved. We are dealing with nuclear transmutations, a physical process. In most of didactic materials, fissile fuel is presented as if it were a common fuel, but it is not or, at least, detailed technical specifications are required (see afterwards). The statement *nuclear is not a typical fuel* is correct (if one considers the field of fossil fuels within which the definition of fuel arose), because nuclear fission is an atomic transmutation (conversion of one chemical element into another according to radionuclide decay rules) and not a chemical process based on a redox reaction, unlike coal, crude oil, and natural gas. While it is not a fossil fuel, and does not emit CO_2 during its energy-generating phase (how carbon-based fuels do), uranium is a finite resource and the transmutation process generates very dangerous (devastating) radioactive waste that is very dangerous and very difficult and expensive to manage in the long term. However, its energy efficiency and lower greenhouse gas emissions have made it—albeit with many reserves—an alternative to fossil fuels. Key differences and critical issues:

- Uranium is a very dangerous and finite mineral resource, so it is non-renewable (as, instead, the sun or wind are), even though it is available in fairly significant amounts;
- Nuclear power plants do not emit CO_2 during energy production [18];
- The process is associated with the production of highly radioactive waste that is extremely difficult to manage in the long term;
- Uranium-235 (less than 1 per cent of the world’s uranium) [18] is a highly efficient energy source, capable of producing large amounts of energy from small amounts of material.

In summary, it can be stated that uranium (and other radioactive elements) is not a fuel in the traditional sense (a burning substance or mixture of substances), but a particular energy carrier that triggers a *physical* process totally different from combustion (Table 1), with:

- A tiny advantage: low CO_2 emissions, and
- Glaring disadvantages: almost unmanageable lethal waste and finite mineral environmental resources.

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Table 1: Classic and nuclear fuels: comparison of some features.

Feature	Fuel	Nuclear Fuel
Energy	Stored in chemical bonds	Stored in nuclei of atoms
Principle	Breaking and reformation of chemical bonds	The nucleus of an atom splits into two or more smaller nuclei (nuclear fission)
Process	Chemical process: redox transformation	Physical process: transmutation
By-products	Gaseous and ash waste (fossil fuels)	Radioactive waste
Driving force	Reaching a lower level of energy (stabilisation)	Reaching a lower level of energy (stabilisation)
Controllability	Easy enough	Highly complex
Plants for use	Simple and cheap	Very complex and very expensive
CO_2 emissions	Present in carbon-based fuels, absent in carbon-free fuels	Low considering the whole lifecycle of a nuclear process
Availability	Wide	Finite
Renewability	It depends on the type of fuel	Non-renewable fuel

Notwithstanding, widening the definition of fuels it is possible to join different energy carriers into a unique broad category of energy providers.

Critical examination of the definition of combustion from a didactic perspective

Combustion is a reactive process in which a fuel and an oxidant (the oxidiser) act as reactants. As previously explained, it is quite difficult to give an exhaustive definition of fuel independent of the concept of combustion. Therefore, product and process are closely interconnected and each of them takes part to defining the other. Many definitions of combustion are focused on thermodynamics and neglect the kinetic aspects associated. Let us look at some of them. According to the Ansys.com website [19]: 'Combustion is a type of chemical reaction between a fuel and an oxidant, usually oxygen, that produces energy in the form of heat and light, most commonly as a flame. Because it produces more heat energy than it consumes, combustion is an exothermic reaction. Since it involves reduction (gain of electrons) and oxidation (loss of electrons), it is also classified as a redox reaction'. Basic explanations of chemistry are correct for an exothermic redox reaction, nevertheless the definition is unsatisfactory, because subtle details able to identify what a combustion is are missing. According to the ChemistryLearner.com website [20]: 'A combustion reaction is an exothermic chemical reaction between substances, usually including oxygen gas and accompanied by the generation of heat, energy, and light (flame). The products of a combustion reaction depend on the combusted substance. When metals and non-metals burn in the presence of oxygen, they will give off their corresponding oxides. On the other hand, hydrocarbons give off carbon dioxide and water upon combustion'. This definition includes useful specifications, but heat and light are forms of energy and, moreover, the flame is made of electromagnetic radiations but also contains gases produced from the vaporisation and chemical breakdown of fuel constituents. The actual contribution of this definition is that it communicates that metals can also be used as combustible substances.

Various details are often missing from the hasty and approximate definitions of combustion available in many textbooks, manuals, slides, and websites. A proposal of definition designed for didactic purposes is the following:

Combustion is a fast, high-temperature, highly exothermic, and self-sustaining redox chemical reaction between a fuel (the reductant) and an oxidant (commonly dioxygen from the atmosphere), that releases more energy than is needed to ignite it.

For educational effectiveness, all these characteristics that define the specificity of the type of chemical reaction that can be called *combustion* must be expressed in the same sentence (like in the one designed for didactic purposes just presented), unless further deepening is carried out immediately. As an example, the meaning of the adverb *commonly* in bracket must be fully explained afterwards (using the repertoire of redox reactions as a model plus specific examples). Concise but comprehensive definitions provide students with a practical study package (milestone of teaching/learning together with concept maps) and allow teachers to require that the definition be assimilated so it can be repeated (within its context, which establishes a network of meanings). For at least two decades, requiring memorisation has seemed an outrage, but abandoning this practice has led, along with other factors, to a significant decline in academic achievement and IQ (the negative Flynn effect [21]).

Ignition is the initial energy to start the combustion process (such as a spark or an electrical current). This is the kinetic aspect of combustion. In the Britannica.com website [22] we can find this specification on kinetic aspects of combustions: 'The rate or speed at which the reactants combine is high, in part because of the nature of the chemical reaction itself and in part because more energy is generated than can escape into the surrounding medium, with the result that the temperature of the reactants is raised to accelerate the reaction even more'. In the Biologyinsights.com website [23] we can find this definition of *fire* providing a specification indirectly regarding the radical mechanism reactions (which is typical of chemical transformations occurring at high-temperature, that provides energy enough to sustain the radical formation process) characterising a combustion reaction: 'Fire is the physical manifestation of a rapid, self-sustaining chemical process called combustion. This exothermic reaction transforms a material, known as fuel, into new chemical substances while releasing a significant amount of energy. This energy is perceived as the heat and light that define a blaze'. In the

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Sustainability.shiksha.com website [24] we can find this specification: ‘Most combustion reactions need an initial spark or flame to get started, but once ignited, the heat generated can sustain the reaction on its own—which is why a campfire keeps burning without constant relighting’.

The *energy* of combustion is primarily released in two forms:

- Heat: Thermal energy that increases the temperature of the surroundings,
- Light: Electromagnetic radiation visible to the human eye.

The flame is the visible radiative manifestation of a fire. Chemically, a flame is composed of gases produced from the vaporisation and chemical breakdown of fuel constituents during combustion. In particular, a flame is composed primarily of hot, glowing gases such as carbon dioxide, water vapour, dioxygen, and dinitrogen; it also contains unburnt fuel particles, soot, and highly reactive free radicals. Combustion is sometimes accompanied by the presence of smoke. Smoke is commonly associated with the combustion of solid fuels (such as wood, coals, wax) and belongs to aerosols, where the dispersion medium is gaseous and the dispersed phase is solid. In particular, smoke is a complex mixture of airborne solid particles, liquid droplets, and gases released when a fuel undergoes incomplete combustion. It primarily consists of carbon (soot), tar, ash, and various volatile substances, appearing grey or black depending on what is burning. The physical-chemistry of dispersed systems (dispersed phase and a dispersing phase) must be recalled, or in any case used, to define the nature of smoke.

In general, redox reactions must be reconsidered as a *chemical model* of reactivity to ensure that students have a foundation for understanding the combustion phenomenon in chemical terms beyond its apparent simplicity (mainly due to everyday experience, so ancestral and clear at a sensory level that it hides the need/opportunity to go deeper, developing an accurate explicative chemical model). In fact, the following redox chemical equations:

fuel + oxidiser → products + energy	
$C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)} + \text{energy}$	fuel = C, coal
$CH_{4(g)} + 2\,O_{2(g)} \rightarrow CO_{2(g)} + 2\,H_2O_{(g)} + \text{energy}$	fuel = CH_4, methane
$2\,H_{2(g)} + O_{2(g)} \rightarrow 2\,H_2O_{(g)} + \text{energy}$	fuel = H_2, dihydrogen

are so simple in themselves, but do not reveal all the key elements for understanding and managing the behaviour of fuels during the combustion process. As specified in [20], different types of fuels involve different types of combustion reactions with different reaction products. In particular, different types of fuels based on their elementary chemical composition (and related different combustion processes) can also be identified:

- Without C: hydrogen (H_2), ammonia (NH_3), carbon-free (or zero-carbon) fuels,
- Based on C and without H: amorphous C (fossil coals and derivatives such as coke and charcoal),
- Containing C and H: crude oil (a natural complex mixture of hydrocarbons) and manufactured derivatives (such as petrol, kerosene, diesel, naphtha, and methane).

Another specification would help students develop a general mental model of combustion based on chemistry. The oxidiser most often encountered is dioxygen present in the air ($O_{2(g)}$), but other chemicals also work. For example, [25] burning dihydrogen ($H_{2(g)}$) with chlorine ($Cl_{2(g)}$) as an oxidiser also produces heat and a flame (hydrogen chloride, $HCl_{(g)}$, is the chemical product formed in excess of oxidiser). It is important to specify that half-reactions not involving dioxygen as oxidant are called oxidations anyway, obviously if we are inside processes with an electron transfer mechanism.

In summary, the set of combustion conditions is collected in an operative model, the so-called *combustion triangle* or *fire triangle*. These locutions include the three factors that must be available simultaneously in space and time for combustion to occur (Table 2):

- Presence of a fuel,
- Presence of an oxidiser,
- Presence of an initial energy (ignition source).

An igniter is a device used to start the combustion process by providing the initial energy (such as a spark or flame) needed to reach the fuel’s ignition temperature (kinetic aspect of the combustion reaction). An igniter facilitates combustion but does not itself provide the bulk of the energy released during prolonged burning. Only the simultaneous presence of these three components can give rise to the fire phenomenon; therefore, the failure of one of them results in its extinction. Once initial energy allows the reaction to start, it continues as long as fuel and dioxygen are present. Ignition is the process of providing the activation energy that is required to initiate a combustion process. An ignition source is defined as any material or condition that provides sufficient energy to ignite vapour fuel, commonly including flames, hot surfaces, electrical equipment, and electrostatic charges.

Identifying and eliminating ignition sources is crucial in preventing fires.

The IUPAC Gold Book—Compendium of Chemical Terminology [3]—does not define combustion, and it is a serious shortcoming. In the well-known textbook of Peter Atkins [26], combustion of glucose ($C_6H_{12}O_6$) is also mentioned:

Table 2: The three components of the combustive phenomenon.

Term	Role in Combustion	Energy Provider Yes/No
Fuel	Substance, or mixture, that burns	Yes, it is the primary source of energy, the energy carrier
Oxidiser	An oxidising substance that reacts with fuel	No, it reacts with fuel to release energy stored in the chemical bonds of the fuel that break
Igniter	Energy supplier initiating the reaction	No, it provides initial activation energy to start the combustion process (kinetic aspect)

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$C_6H_{12}O_{6(aq)} + 6\ O_{2(g)} \rightarrow 6\ CO_{2(g)} + 6\ H_2O_{(l)}$ + energy

to remember that the term *combustion* can also apply to the biological burning of monosaccharides ($C_6H_{12}O_6$) inside the mitochondria of cells (aerobic cellular respiration, a multi-step process that converts the chemical energy in glucose into ATP, adenosine triphosphate).

Hence, *combustion* is a paramount process bridging many subfields in chemistry, such as organic, inorganic, industrial chemistry, and biochemistry—all linked by the energy production that allows organisms or mechanisms to run.

Metals as fuel

A niche is that of metals used as fuel. The topic dates back to the early 19th century with the discovery of the magnesium flash, the *photochemical effect* used in photography. The combustion reaction between Mg powder—the fuel—and dioxygen is:

$2\ Mg_{(s)} + O_{2(g)} \rightarrow 2\ MgO_{(s)}$ + energy

The growing demand for sustainable, large-scale energy storage has sparked significant interest in metal fuels, such as aluminium, iron, magnesium, and zirconium, as high-energy-density, carbon-free alternatives to fossil fuels [27]. In particular, iron powder is studied as a circular energy carrier [28]. When burned, it releases high-temperature heat without any carbon emissions. At a didactic level is not so rare to deal with statements like this [29]: 'With iron, the leftover product after combustion is iron oxide, more commonly known as rust. No carbon dioxide is produced, and the rusty iron can be easily collected as it doesn't form a gas – burning iron emits no noxious gases at all. Iron rust can even be processed to remove the oxygen and return it as iron using hydrogen. Three remarkable mistakes can be identified:

- The reference to *iron oxide* is wrong; the oxidation state of iron in the compound is omitted (iron oxides would instead have been acceptable as a general chemical name for a class of related compounds). This mistake is unfortunately widespread (also in school textbooks and specialist essays, for example, on paint pigments).
- Iron oxides of every oxidation state do not necessarily coincide with rust, being rust a complex mixture based on the probable predominance of $Fe_2O_3 \cdot nH_2O$, hydrated ferric oxide (the actual composition of rust depends on the environment in which the iron-based artefact degraded).
- Carbon dioxide (CO_2) is not a noxious gas but a vital compound giving rise to the essential carbon cycle (a biogeochemical cycle divided into inorganic and organic based on the chemical form of carbon) in the environment.

The term *rust* is used in folk speeches as a blanket term for all iron-oxygen compounds to indicate material or immaterial degradation (think of Neil Young & Crazy Horse's landmark 1979 album *Rust Never Sleeps*), but in a didactic and outreach meaning this is really inappropriate because misleading.

Terminological flattening is the primary enemy of a good lesson at any level of education.

Two chemical phenomena are confused as if they were superimposable in [29]:

- The *slow*, spontaneous, exothermic environmental degradation of iron-based artefacts by dioxygen and humidity at room temperature; the core step is: $4\ Fe_{(s)} + 3\ O_{2(g)} + 6\ H_2O_{(l)} \rightarrow 4\ Fe(OH)_{3(s)}$ + energy,
- The *fast*, controlled, exothermic combustion of iron powder (fine granules to foster the kinetic side of the transformation) at high temperature: $4\ Fe_{(s)} + 3\ O_{2(g)} \rightarrow 2\ Fe_2O_{3(s)}$ + energy (note: $Fe_3O_{4(s)}$ can also be formed).

This is a direct way to confuse students in an already complex subject, chemistry, full of exceptions and special cases and subcases, compared to the predictable trends based on the periodic table and the few available laws. It must be still specified that *dry corrosion* (also called *chemical corrosion*) of iron also exists, it occurs at high temperatures (> 200 °C and particularly rapid at temperature values > 700 °C) without humidity or water as an electrolyte and produces iron oxides (Fe_2O_3, FeO, Fe_3O_4) on the *surface* of the artefact (a metal oxides layer is formed). Therefore, dry corrosion of iron (or some iron-based alloys) does not produce rust but iron oxides (anhydrous binary compounds), and, therefore, stating sharply that the product of iron combustion is rust remains an error. At most, some analogies can be observed between oxidative processes of iron that occur, albeit in totally different circumstances, at high temperatures and that produce oxides as reaction products. It is also important to emphasise that iron corrosion, at any temperature, is a superficial phenomenon, whilst combustion occurs in equipment designed to maximise reaction yield by involving the entire iron bulk. Rusting vs. Burning: while both processes involve exothermic iron oxidation to form Fe_2O_3 as a very first step of transformation (net of the initial appearance of Fe^{2+} compounds), rusting usually refers to a slow, surface, moisture-dependent oxidation at room temperature, whereas combustion refers to a bulk, rapid reaction hindered or extinguished by water (a summary of distinctive features is collected in Table 3).

The chemical focus is: when a substance chemically combines with dioxygen, the related chemical process is called *oxidation*; it is a half-reaction that crosses with a reduction half-reaction to give rise to a redox chemical reaction (the full process). In the case of iron, this oxidation can occur in different scenarios that configure it:

- As a perishable metallic object in the environment (therefore requiring protection), or
- As a metallic combustible powder used in a controlled way within combustive devices.

In both cases, the iron undergoes an oxidation half-reaction, which is the only aspect in common that has to be

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Table 3: Rusting vs. burning of iron: summary of main differences.

Feature	Iron Burning	Iron Rusting
Speed	Very Fast (instant)	Very Slow
Temperature	Very High	Room
Process	Provoked in appropriate devices	Spontaneous in the environment
Phenomenon	Massive	Surface
Water	Unnecessary	Necessary
Main Reaction Products	Fe_2O_3, Fe_3O_4 (anhydrous compounds)	$Fe_2O_3 \cdot nH_2O$ (hydrated compound)

clearly evidenced using redox reactions as an explicative chemical model. Iron combustion (burning) and iron corrosion (rusting) can be indicated to students as processes that have in common redox chemical reactions of iron, but that's it. Moreover, $Fe_2O_3 \cdot nH_2O$ (reddish-brown coloured, Fe^{3+}) is only one of the first compounds resulting from iron degradation. Rust is commonly a *mixture* of hydrated ferric oxide with hydrated ferrous oxide ($FeO{\cdot}nH_2O$, greenish-white coloured, Fe^{2+}), magnetite (Fe_3O_4, black coloured, Fe^{2+} and Fe^{3+}), and, in the presence of CO_2 in the atmosphere, basic ferric and ferrous carbonates too. The ratio Fe(II)/Fe(III) is regulated by dioxygen availability. Clearly, the composition of each individual rust depends on the environmental conditions in which it forms. The complete overlapping of combustion and rusting of iron, as if they were phenomena representable by the same identical chemical equation, is simply one of the drastic and senseless simplifications resulting from ignorance and superficiality that should be banned from teaching practices at any level of education.

Language and terminology in the teaching approach

The first pillar on which a lesson, at any level of education, is built is *language*. Students should be exposed to contextualised language, especially in scientific disciplines where it is essential to draw a clear boundary between everyday and scientific language. Many words are polysemous, and many words are used improperly in everyday life, precisely because ignorance in the scientific field is rampant. If this ignorance is allowed to enter the classroom and make its home there, any attempt to build correct scientific models of phenomenal reality with the students will be in vain. Precisely because the constructivist approach to learning requires each student to be the architect of the structuring of their mental models, the raw material provided by the teacher must be linguistically impeccable in every aspect, thus minimising grey areas in the lesson. These core concepts are well expressed and remarked in the review by Mönch and co-workers regarding the scientific language in education [30]. In the abstract of this review, we can read: 'Since students' knowledge of scientific language can be one of the main difficulties when learning science, teachers must have adequate knowledge of scientific language as well as the teaching and learning of it'. To promote scientific literacy, care for language is fundamental, as in every field of teaching. Unfortunately, in the current technocratic society, words are often treated as if they were toys. Schools and universities are the guardians of the language, and they must sensitise and train students to pay attention to the use of words in relation to general and sector dictionaries they use during their studies.

Selecting the right word in any sentence for any purpose is not a game.

The world is made of words, as Terence McKenna (American philosopher, ethnobotanist, lecturer, and author, 1946 – 2000) stated: 'The syntactical nature of reality, the real secret of magic, is that the world is made of words. And if you know the words that the world is made of, you can make of it whatever you wish'. Sir Richard Charles Nicholas Branson (British entrepreneur): 'The world is made of words. And if you know the words that the world is made of, you can make of it whatever you wish'.

The idea, according to which teaching scientific disciplines can be done regardless of care for language (both general and technical), is totally wrong and misleading [31]. Certainly, it is important to explore before explaining to investigate the preconceptions [32] and misconceptions that act as a filter/barrier to correctly learn new terms and concepts (which must be harmoniously allocated in each student's previous cognitive map).

Classroom is the place where proper language flourishes, so students will become ambassadors in the societies of a well-structured language, useful as a shield against manipulation, which is commonly administered with a distorted use of words. No practical experience, however important, can guarantee effective long-term learning without a solid knowledge of the language.

The linguistic sloppiness promoted by social media is causing a deterioration in education.

Each teacher is responsible for showing their students a different world, made up of carefully chosen words to compose fluent sentences that structure frank and sharp communication that is less exposed to ambiguity. Brain-based learning has emerged as a significant paradigm that aligns teaching strategies with the underlying cognitive and emotional characteristics. Brain-based learning represents a paradigm shift in pedagogical approaches, moving from traditional, content-centric models to learner-centric methodologies aligned with current understanding of neurophysiology and cognitive science. Many peer-reviewed papers deal with methodologies and strategies used to advance the integration of brain-based learning within science classrooms, as described by the review in [33]. Obviously, brain-based learning is especially relevant in the context of primary education, a critical developmental stage characterised by high levels of neuroplasticity that make children particularly receptive to new learning, including language acquisition [34]. Despite this, the poverty in chemistry knowledge is discouraging on average and reveals the ineffectiveness of current chemistry teaching methodologies, a bad social influence of chemistry narrated by the mainstream on students, or the scarcity of space reserved for it in today's schools. In some cases, it can also be considered significant that high schools teach integrated scientific subjects containing chemistry, maybe just

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for one or two years, and that school teachers often do not have a master's degree in chemistry.

Conclusion

This paper addresses a fundamental topic in industrial chemistry, the teaching of which is based on a broad set of prerequisites and, in general, on a good knowledge of basic chemistry. The subject of fuels and combustion is of interest to both high school and university students. In particular, the paper focused on the terminological and linguistic aspects that contribute to structuring the definitions of fuel and combustion, with an extensive analysis of the definitions found in various sources such as textbooks, handbooks, slides, and websites. The aim is to contribute to improving the quality of chemistry teaching by considering a topic of clear interest to students, given its relevance to everyday implications. The critical examination of the current teaching approach on fuels and combustion allows to identify various weaknesses. As a consequence, new definitions—more suitable to avoid grey areas of the lessons (high schools and universities)—are proposed. The main goal of this paper is to promote accurate communication regarding the subject of fuels and combustion, while also overcoming inconsistencies (detrimental to the quality of any communication) detected in many sources on fuels, nuclear fuel, and combustion. Some considerations are also developed on the apparently superimposable processes of iron burning and rusting, introducing subtle but precise elements of distinction between the two processes. The main aim was to clear the fields of teaching and outreach of the many approximate, interpretable, ambiguous, shallow, or decidedly erroneous contents and to make the exposition of a topic so important for humanity's survival and students' acculturation fluid, lean, and scientifically correct.

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