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RESEARCH PAPER

A critical evaluation of the safety datasheets of graphene materials

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Abstract Graphene, a single layer of carbon atoms, is a material that has held a leading position in material research owing to its excellent properties, allowing its use in innovative technologies. In spite of many advantages, the graphene's potentially hazardous effect on the environment as well as human health constitutes a major drawback. Year after year, safety data sheets (SDS) constitute the main reference on a material's potential hazards and the methods to prevent or address them if needed. However, SDS content has been heavily criticized due to incomplete, incorrect, or missing information and the cost required to produce and maintain it. The primary objective of this work is to introduce a stepwise process of knowledge management regarding SDSs, by identifying unexplored or neglected sections in a holistic approach. In this light, this work examines 37 graphene SDS, using modified Hodson's criteria. The quality evaluation revealed that approximately 5% (2/37) of the datasheets were deemed reliable without restrictions (excellent), the majority 49% (18/37) were categorized as reliable with restrictions (good), while about reaching almost 46% (17/37) were deemed non-informative. It is noteworthy that approximately 73% of the SDS require major improvements; thus, the majority did not provide adequate data to be properly assessed. Section 15 could potentially trigger fundamental changes in the product status. The comprehensive evaluation of all 16 sections will enhance the capacity to conduct research mapping and formulate opinions on nanomaterials, thereby stimulating innovation.

Keywords Graphene · Material safety data sheets · Hazards · Evaluation · Section · Nanomaterials · Environmental and health effects

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Introduction

In the new global economy, appears to be a top priority on the global scientific and manufacturing agenda, promoted by many as the next industrial evolution [1, 2]. There is a vast variety of available materials worldwide that are used in numerous applications throughout daily life [3]. Since its discovery in 2004, graphene has been deemed as one of the most impactful scientific and technological accomplishments [4]. Its monolayer of graphite (with carbon-to-carbon bond distance in the range of 0.14 nm) has been under the spotlight ever since [4-6]. Graphene exhibits improved physical properties compared to other alternatives, such as electron mobility and high thermal conductivity [7, 8], high Young modulus levels [9], larger surface area [10], and improved electrical conductivity and optical transparency [11]. In view of the increased scientific interest, the potential applications of graphene have been heavily researched. Furthermore, both graphene and its derivatives have been evaluated for their capacity to manage pollution such as via gas adsorption [12].

Despite their successful applications, there is now extensive scientific literature regarding the necessity of nano-specific information with unique performance, such as graphene materials. Although their potential toxicity has been highlighted, there are few studies on their impact on human health [13]. Safety Data Sheets (SDS) are the main mechanism for communicating information regarding the safety and risks of chemicals [14]. They are relatively simple, brief documents (frequently less than 10 pages) that summarize critical identifiers about a specific substance [15]. There are currently numerous publications about SDSs, ranging on their definition [16], their indented audience [17], the manner they are used [18-20], and capturing the technical details in an easy-to-use search engine. The research to date has tended to focus on the way SDSs can capture and communicate the nanomaterials' nature, replying to different guidelines like ISO TR 13,329, ECETOC TRA, and GHS implementations [18, 20-26] worldwide, reporting the important problem of missing "nano-specific" information, such as toxicity, physicochemical information, and precautionary measures. In Europe, the content of SDS is regulated by guidelines established under the Registration, Evaluation, Authorization and Restriction of Chemicals Regulation (REACH). REACH and the Classification Labeling and Packaging Regulation also incorporate the additional requirements provided by the United Nations, via the Globally Harmonized System for the Classification and Labeling of Chemicals (GHS), which offers a global standard about the mandatory data to include in a SDS [19]. The proposed guide suggests a 16-section format, where the exact hazards related to the material are mentioned in the second section of the SDS, while the material's physicochemical properties are recorded in Sect. 9 [27].

Despite the advancements made in community maturity, reduction of knowledge gaps, and establishment of safety protocols and controls in laboratories and workplaces, safety datasheets remain an unresolved issue. Three persistent issues have been identified.

The generation and upkeep of Safety Data Sheets and associated labels entail substantial expenses for all parties involved [14]. Despite the establishment of rigorous chemical risk assessment protocols over the course of three decades and the subsequent development of similar timelines for risk assessments in other fields [28], there remains a lack of standardized methods for companies to effectively manage Safety Data Sheets (SDSs). As a result, concerns persist regarding issues such as consistency and missing information, even after nearly four decades since the issuance of the Hazard Communication Standard [14]. There exists a notable disparity between the time required for risk assessment to adhere to REACH regulations, such as conducting chronic exposure studies for novel applications of nanomaterials, and the timeline for bringing these materials to market. Moreover, the associated costs of conducting such tests are also considerable [29].

Second, the costs of different SDS sections vary significantly due to the complexity of the information and the time required to obtain it (Fig. 1).

Almost two decades ago, discussions began on the fundamental issue of the cost of nanomaterials. According to Miller's report in 2005, research and development costs for nanoscience endeavors are very high, as are the resources needed to commercialize products [30]. Various studies in literature highlight the importance of cost. In 2007, Owen et al. underscored the importance of factoring in the cost burden of regulatory testing in health and safety regulations, as it serves as a critical determinant in prioritizing the risks associated with nanoparticles [31]. According to Choi et al., initial projections indicate that the process of developing and conducting quantitative risk assessments for nanomaterials and tested products could incur costs ranging from US$249 million to US$1.18 billion and could take anywhere from 24 to 53 years to complete [32].

Third, Anne DeMasi has noted that while risk information for particular chemicals does not change often, environmental and regulatory policies get updated much more frequently. Environmental and regulatory requirements are required for Sects. 12–15, but these sections are not mandatory according to the 2012 Hazard Communication Standard [14] (Fig. 1). The significance of environmental protection extends

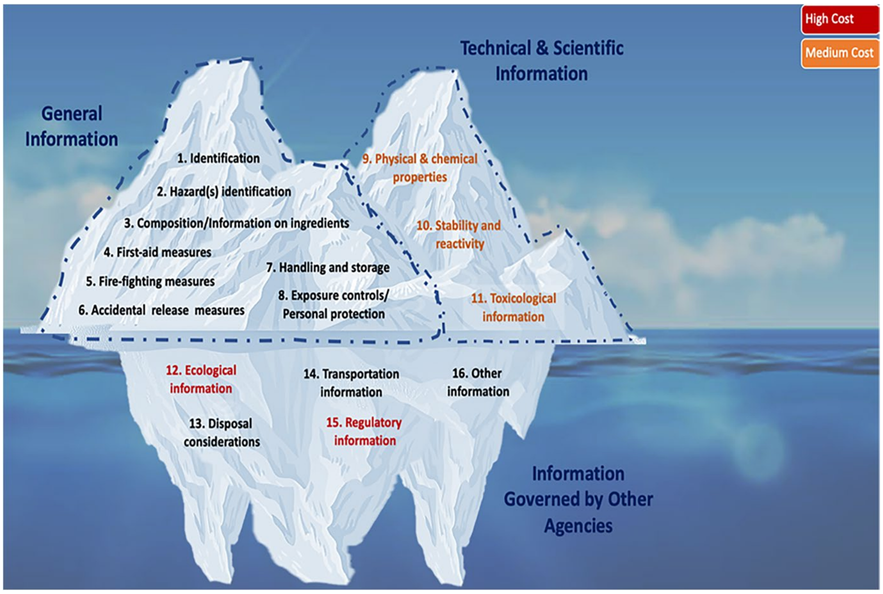

Fig. 1 Exploring uncharted sections of SDS

beyond technological and biochemical considerations, encompassing economic aspects as well. There exists a close interconnection between economic and environmental factors, as evidenced by these associations [33].

The reliability and accuracy of SDS assessments have been significantly compromised by the influence of the latter. In addition to the vast quantity and variety of nanomaterials, it is important to keep in mind that nanomaterials are highly heterogeneous in terms of their physicochemical properties, making their assessment a challenging task. The objective is thus to examine 47 MSDSs for graphene and graphene-based products, utilizing a scalable stepwise strategy. The resulting insights from this effort, particularly in unexplored sections, will be reflected upon. The scope of this study entails a quantitative evaluation of all sections, with the goal of obtaining a strategic management perspective by creating a holistic profile.

Methodology

The triangulation research approach was utilized in this study, employing a combination of qualitative and quantitative methods, as well as diverse data sources. To get past this challenge, a four-step procedure (Table 1) has been adopted, in order to create a dataset of "codified graphene and graphene-based SDS".

Filling the knowledge gaps

During the research clarification, the primary aim was to gain a clear understanding of the research objective that is both realistic and worthwhile to pursue. This was accomplished through an extensive literature review, which focused on identifying the factors that influence the objective and its potential success, particularly the relationship between them. An initial representation of the current state was recorded, along with the intended outcome, to clearly articulate the underlying assumptions for each description.

Collecting data and envisioning an improved scenario

In STEP II, following the establishment of a clear research objective, a descriptive study was conducted to identify the Safety Data Sheets (SDS) for graphene. The first phase of the process required visiting the material vendors sites and looking up the SDS for graphene and graphene derivatives. More specifically, the selected vendors were chosen due to producing or re-selling graphene, graphene oxide (GO), or reduced GO (rGO). Each vendor offers the SDS as publicly available information that can be downloaded, while in some cases, they were procured after sending

Table 1 Stepwise methodology

Steps		Goals	Method	Result
Filling the knowledge gaps	I	Holistic evaluation of the SDS	Literature search	Identify the potential of the unevaluated sections
Collecting data and envisioning an improved scenario	II	Find and obtain graphene SDS	Vendors search	Graphene SDS, technical data sheets
Designing SDS knowledge management	III	Group/filter and study graphene SDS	Application of filtering criteria (via creation/revision date and written language—English)	Grouping/filtering of graphene MSDS
Classification of SDS	IV	Segmentation of the SDS	Modified Hodson (Modified Klimisich and Eastlake)	Codified graphene MSDS
Recommendations for decision making				(a) Uncovering information on product status from Sect. 15 for the graphene products (investigational vs. semi-commercial) (b) Identification of the optimal SDS

email requests to the vendor. Follow-up emails were sent after two weeks to ensure that the request would be addressed, when the initial request garnered no response. The reliability of each document was assessed depending on how accurate the provided information was, the amount of provided detail, and pre-existing understanding of a material's properties and behaviors. One SDS was taken into account per studied graphene-based nanomaterial by each vendor. This process resulted in an initial sample of 109 SDS, obtained from $n=90$ vendors that will act as the basis for a more in-depth evaluation.

Designing SDS knowledge management

This was achieved through qualitative analysis of the obtained datasheets in order to identify the types of risks linked to the studied materials. The outcome underlined the need to study the SDSs in segments and further analyze them and evaluate their structure and what information is considered mandatory. Additional criteria such as regularity of updates to the SDS content were examined. When more than one version of a document was retrieved in the sample, the most recent one was selected for further evaluation, to ensure it contains the most up-to-date information. Furthermore, datasheets without a creation/revision date or when the revision took place more than four years ago were excluded from the sample. In addition, the language of all studied SDSs was English. After this screening process, 15 out of the 109 SDS were eliminated due to the absence of revision date. In effect, all the studied SDSs were created or revised after 2019. Lastly, one last exclusion criterion was the size of the particle of the substance. The final sample consisted of 37 SDS, obtained only from suppliers with compliance requirements in the EU, USA, UK, or Canada.

Classification of SDS

The fourth phase of the process was the evaluation of the SDSs using the Hodson et al. [20] method. More specifically, the SDS were evaluated based on the modified Klimisch et al. [34] criteria, applied on eleven (out of sixteen) datasheet categories and the four questions of the Eastlake et al. ranking system. The Klimisch et al. standard examines the quality of toxicological and ecotoxicological data to determine if they are reliable, relevant, and adequate, assigning a numerical code for each category. Based on Klimisch's coding principles, Hodson et al. [20] provided a ranking scheme appropriate for nanomaterial's SDS evaluation according to which the highest score a SDS can receive is 64, i.e., a maximum 4 per category, multiplied by the 16 categories, while the lowest is 32. Using this system, the calculated scores can be categorized as excellent (ranging between 56 and 64), good (ranging between 47 and 55), and required major improvement (scores between 32 and 46).

The four questions of the Eastlake [18] approach, that the datasheets were evaluated on are:

1. Did the SDSs explicitly mention that the substance is in the nanoscale using a numerical system?
2. Did the SDSs mention any Occupational Exposure Limit for the larger versions of the material, and was there any information provided about the applicability of this limit to the nanosized form?
3. Did the SDSs reference particular toxicity-related data or information about the nanoscale version of the material and did it mention that the bulk versions may not have the same toxicities as the nanoscale forms?
4. Did the SDSs propose the use of PPE etc., in cases where exposure was possible?

Upon evaluating the datasheets using both methods, those that did not fail any or only one category were classified as "satisfactory." Datasheets with missing information in two categories were labeled as "in need of improvement." Lastly, if a datasheet failed in three or more categories, it was categorized as "in need of significant improvement." For the purposes of this work, the scoring information for each section, and then the total achieved for each datasheet are presented in Table 2. The datasheets were evaluated by the co-authors separately, and if there were any differences of opinion, an agreement was reached to assign the score.

Since this ranking model required to check whether toxicity data was provided and the Haz-Com standard mentions that there is no need for chemical testing, using just the Eastlake et al. system would not be sufficient for the assessment; thus, the Klimisch et al. approach received the most focus in this case.

Recommendations

Recommendations for the commercial status for the graphene products (investigational vs. semi-commercial) through Sect. 15 (b) Identification of the optimal MSDS were provided for decision making.

Results

A final sample of 37 SDSs for graphene-based nanomaterials were retrieved from producers and classified using the modified Hodson et al. method. The assessment results indicated that approximately 5% (2/37) of the datasheets were deemed reliable without restrictions (excellent), the majority 49% (18/37) were categorized as reliable with restrictions (good), while about reaching almost 46% (17/37) were deemed non-informative (Table 3).

The datasheets that were revised between 2019 and 2020 were found to be 60% non-informative, 40% reliable with restrictions while those revised after 2021 were deemed approximately 36% non-informative, 55% reliable with restrictions, and 9% reliable without restrictions. None of the assessed SDSs managed to get a maximum score (64), as the highest reached was 57 points, due to missing specific toxicological and OEL data. The lowest score reached was 37, due to containing very generic statements such as to "follow general industrial hygiene practices," or that there is "no data available." Applying the second pillar of Hodson's evaluation system, the outcome for 2019–2022 was 38% in need of significant improvement, 32% in need of improvement, and 30% satisfactory.

Figure 2 presents a breakdown of the SDSs according to reliability ranking, grouped per revision year. For the first group of SDSs, i.e., those created or revised during 2019–2020, the final ranking was 60% in need of significant improvement, 27% in need of improvement, and 13% satisfactory.

Safety data sheets that were created or revised over the last two years seem to score better when

Table 2 Scoring criteria for the datasheet sample

SDS section #	Section headline		Minimum regulatory requirements- GHS vol9	Validation categories and ranking criteria (points)		
	Eastlake (X)	Modified Kimlisch by Hodson (O)		Excellent (4 points)	Good (3 points)	Requiring major improvements (2 points)
1	Identification of the material and the vendor X	O	•GHS product identifier •Alternative identification methods •Recommended uses and potential restrictions •Supplier's details (including name, address, phone number, etc.) •Emergency phone number	All required information is available (e.g., *"CAS number: 1034343–98-0", "Additive for varnishes and paints"*)	Lack of one of the required identifiers	Lack of two or more of the required identifiers
2	Hazards identification	O	•GHS classification, including any local or national information •GHS labels, along with the precautionary statements •Other risks that are not subject to the GHS	Provides the chemical composition and references particular risks, GHS/CLP classification (e.g.," *Eye Irrit.: H319-Causes serious eye irritation")*	A precautionary H statement is not mentioned	Generic statement (e.g., *"no hazardous")*
3	Composition/information about the substance's ingredients X	O	•Chemical identity •Commonly used name or potential synonyms •CAS number and any other identification alternatives •Existence of potential impurities and use of stabilizing additives, whose classification should be included in the classification of the substance	Complete information (e.g., "*graphene CAS# 1,034,343–98-0: 99% w/w*")	Lack of one required element	Lack of two or more of the required identifiers

Table 2 (continued)

SDS section #	Section headline		Minimum regulatory requirements- GHS vol9	Validation categories and ranking criteria (points)		
	Eastlake (X)	Modified Kimlisch by Hodson (O)		Excellent (4 points)	Good (3 points)	Requiring major improvements (2 points)
4	First-aid measures	O	•Identification of mandatory measures, categorized based on exposure routes •Most significant/frequent symptoms, either immediate or delayed •Mention any immediate measures required potentially special treatment where applicable	Complete information regarding eye, skin, ingestion, and inhalation exposure routes (e.g., "*Rinse eyes thoroughly with.. for at least 15 min… Do not allow the person affected to… If the injured person uses contact lenses… a doctor should be consulted as quickly as possible with the SDS of the product*")	Lack of one required element	No information or poorly described first-aid measures(e.g.: "*..(see Sect. 2.2) and/or in Sect. 11*", "*In case of Eye contact: Flush eyes with water.")*
5	Firefighting measures	O	•List of appropriate and inappropriate to use extinguishing means •Particular hazards derived from the material •Specialized protective equipment and precaution measures for fire-fighters	There is a statement regarding the potential occurrence of combustion or explosion (e.g., "*In the event of combustion.. this material may release carbon monoxide (CO) or… At temperatures over 180- 300 ºC, this material may react with potassium, sodium, rubidium…may react explosively with water*", [2]" *Fire-fighters should wear…conforming to European standard EN 469 will provide a basic level of protection for chemical incidents")*	Generic statement without special instructions about nanomaterials (e.g., *"Special hazards arising from the substance or mixture: Carbon oxide")*	No statement provided

Table 2 (continued)

SDS section #	Section headline		Minimum regulatory requirements- GHS vol9	Validation categories and ranking criteria (points)		
	Eastlake (X)	Modified Kimlisch by Hodson (O)		Excellent (4 points)	Good (3 points)	Requiring major improvements (2 points)
6	Accidental release measures X	O	•Personal precautions, PPE, and emergency measures •Environmental precautions •Containment and cleaning	Advice about using HEPA vacuums and avoiding the creation of dust or using aerosols (e.g., "*Use particle filters (HEPA H14) when extracting at the source", "..collect and place in suitable waste disposal…Small Spillages < 10kgs: remove spillage with a vacuum cleaner or…Large spillages:..")*	Only generic instructions were provided (e.g., "*Spilled or released material should be collected mechanically and disposed of in suitable containers.")*	No statement provided
7	Handling and storage	O	•Precautions for safe handling •Conditions for safe storage, including any incompatibilities	Offers information about handling and storing the material safely (e.g., "*Keep only in…Keep away from…Keep the container tightly closed and…Avoid contact with… Use containers made of…should be stored in labeled closed containers in….avoid creating accumulations or concentrations of dust since any dust can form a potentially explosive mixture in air. Graphene is electrically conductive. Care should be taken…*")	Lack of either handling or storage instructions	No statement provided

Table 2 (continued)

SDS section #	Section headline		Minimum regulatory requirements- GHS vol9	Validation categories and ranking criteria (points)		
	Eastlake (X)	Modified Kimlisch by Hodson (O)		Excellent (4 points)	Good (3 points)	Requiring major improvements (2 points)
8	Exposure controls/personal protection		•Control parameters (occupational exposure limits) •Suitable engineering controls •Individual protection steps, such as use of PPE	OEL/REL reference for nanomaterial, along with details on the use of engineering controls and PPE (e.g., "*isolate danger areas (through partitioned rooms, working in the glove box),*" *"BS EN 14,042:2003… MDHS14/3 General methods for sampling…", "Reference should be made to monitoring standards, such as the following: European Standard EN 689 (Workplace atmospheres…",* "Provide adequate general and local exhaust ventilation..")	No OEL/REL reference, generic statement about engineering control and PPE use without details (e.g.," *OEL Substance: Graphite: ACGIH (TLV): 2.0 mg/m3 respirable"*)	No statement provided regarding occupational exposure limits, engineering controls, or requirements to use PPE
	X	O				

Table 2 (continued)

SDS section #	Section headline		Minimum regulatory requirements- GHS vol9	Validation categories and ranking criteria (points)		
	Eastlake (X)	Modified Kimlisch by Hodson (O)		Excellent (4 points)	Good (3 points)	Requiring major improvements (2 points)
9	Physical and chemical properties X	O	•Physical state, color, and odor •Melting and freezing point •Boiling point and range •Flammability—lower and upper explosion/flammability limit •Flash point •Auto-ignition and decomposition temperatures •pH •Kinematic viscosity and solubility •Partition coefficient: n-octanol/water (log value) •Vapor pressure •Density and/or relative vapor density •Particle attributes	Complete information provided (e.g.," *Density at 20 ºC: 2258,2—2318,2 kg/m*^{3}")	Generic statement without detailed information (e.g., "melting point-3800^{0}C")	No statement provided

Table 2 (continued)

SDS section #	Section headline		Minimum regulatory requirements- GHS vol9	Validation categories and ranking criteria (points)		
	Eastlake (X)	Modified Kimlisch by Hodson (O)		Excellent (4 points)	Good (3 points)	Requiring major improvements (2 points)
10	Stability and reactivity	O	•Reactivity and stability •Potentially hazardous reactions •Conditions that should be avoided •Materials that are not compatible with •Hazardous decomposition produc	Reference to conditions that should be avoided (e.g., *"At temperatures over 180 ºC, this material may react with potassium…may react explosively with water", "TGA shows major decomposition at 185 C…some decomposition may occur…The substance is hygroscopic and will absorb water by contact with the moisture in the air…")*	Generic statement without detailed information (e.g., "*stable under normal conditions," "no special reactivity has been reported")*	No statement provided
11	Toxicological information X	O	A succinct but thorough description of the potential toxicological (health) impacts and the available data required to determine such effects: •Frequent exposure routes (such as inhalation, ingestion, etc.) •Symptoms linked to the physicochemical and toxicological attributes •Delayed, immediate or chronic results stemming from short- and long-term exposure •Numerical depiction of toxicity levels	Referenced toxicological data provided for both acute and chronic exposure (e.g., *"Potential chronic health effects: Substance: Graphene/ Result: LD50 Oral [OECD 420]/ Species: Mouse—Male, Female/ Dose: > 5000 mg/kg/ Exposure: -/Remarks: Mortality: None")*	•••Generic toxicological information without details (e.g., "toxic," "safe if properly used," "*Irritant effect on eyes: slight irritant*"")	No statement provided

Proposed modifications in Hodson's ranking criteria

Table 2 (continued)

SDS section #	Section headline		Minimum regulatory requirements- GHS vol9	Validation categories and ranking criteria (points)		
	Eastlake (X)	Modified Kimlisch by Hodson (O)		Excellent (4 points)	Good (3 points)	Requiring major improvements (2 points)
12	Ecological information		A complete and comprehensive description of environmental properties and the available data used to identify these properties ●Toxicity ●Persistence and degradability ●Bioaccumulative potential ●Mobility in soil ●Other adverse effect	Referenced nano-specific ecotoxicological data (e.g.," *"Toxicity: Substance: Graphene/ Result: Acute EC50 62.2 mg/l [OECD 201]/ Species: Algae-Chlorella pyrenoidosa/ Exposure: 96 h/Remarks:- ", "This substance contains no components considered to be either persistent, bioaccumulative and toxic (PBT) or very persistent and very bioaccumulative (vPvB) at levels of 0.1% or higher")*	Generic ecotoxicological information without details (e.g., "*No data available This product is being distributed for R&D purposes, as such toxicological data has not yet been gathered," "No known significant effects or critical hazards")*	No statement provided

Table 2 (continued)

SDS section #	Section headline		Minimum regulatory requirements- GHS vol9	Validation categories and ranking criteria (points)		
	Eastlake (X)	Modified Kimlisch by Hodson (O)		Excellent (4 points)	Good (3 points)	Requiring major improvements (2 points)
13	Disposal considerations		Provide information for appropriate disposal, recycling, or reclamation of the nanomaterial and/ or its container to assist in the determination of safe and environmentally preferred waste management options consistent with the requirements of the national competent authority •Specify disposal containers and methods •Discuss physical/ chemical properties •Discourage sewage disposal •Identify special precautions for incineration or landfill	Subsections are sufficiently completed (e.g., "*…this product is not regarded as hazardous waste, as defined by EU…, "Type of waste (Regulation (EU) No 1357/2014): HP5… ", "Consult the authorized waste service manager… in accordance with Annex 1 and Annex 2 (Directive 2008/98/ EC)…. We do not recommend disposal down the drain...This material and its container must be disposed of in a safe way… Empty containers or liners may retain some product residues… Avoid dispersal of spilt material and runoff and contact with soil, waterways, drains and sewers")*	Generic statement without detailed guidelines (e.g., "Recycle to process, if possible…. Consult your local, regional authorities…." "Observe all federal, state, and local regulations when disposing of the substance.")	No statement provided

Table 2 (continued)

SDS section #	Section headline		Minimum regulatory requirements- GHS vol9	Validation categories and ranking criteria (points)		
	Eastlake (X)	Modified Kimlisch by Hodson (O)		Excellent (4 points)	Good (3 points)	Requiring major improvements (2 points)
14	Transport information		Basic classification information for the shipment of a hazardous substance by road, rail, sea, or air ●UN number ●UN proper shipping name ●Transport hazard class(es) ●Packing group (if applicable) ●Environmental hazards ●Special precautions for user ●●●Transport in bulk according to IMO instruments	Subsections are sufficiently completed (e.g., "*Not classified as a dangerous good for transport under DOT, IMDG, ADR, RID, or ICAO/IATA*")	Generic statement without detailed guidelines (e.g., "*Not a hazardous material for transportation*")	No statement provided
15	Regulatory information		●Safety, health, and environmental legislation specific to the material in question, which is not already indicated elsewhere in the SDS ●Whether a chemical safety assessment (CSA) has been carried out	Complete *regulatory* information (e.g., "*All components of this product are listed in the U.S. Environmental Protection Agency Toxic Substances Control Act Chemical Substance Inventory*")	No detailed description of products' regulatory and commercial status. Information provided only for followed legislation	No statement provided

Table 2 (continued)

SDS section #	Section headline		Minimum regulatory requirements- GHS vol9	Validation categories and ranking criteria (points)		
	Eastlake (X)	Modified Kimlisch by Hodson (O)		Excellent (4 points)	Good (3 points)	Requiring major improvements (2 points)
16	Other information, including information on the preparation and revision of the SDS		Relevant information that has not been included in the previous sections: •Date of preparation of the latest revision of the SDS •Clear indication of changes that occurred after the last revision •Abbreviations and acronyms used in SDS •Literature reference and sources of data used in SDS •Relevant risk phrases, hazard statements •Advice on training for those handling the chemical •Disclaimer	All subsections have been covered (e.g., "*Minimal training is recommended to….*", *"Texts of the legislative phrases mentioned in Sect. 2: H319… H335: May cause respiratory irritation*", "Principal bibliographical sources: ttp://echa.europa.eu, http://eur-lex.europa.eu"')	Only the date of preparation/revision and disclaimer subsection is covered	No statement provided

Table 3 Overview of the assessment results using Hodson et al. approach

Dual ranking scheme	No SDS/%	2019–2020 $n=15$	2021–2022 $n=22$	2019–2022 $n=37$
Modified Klimisch's validation scoring system	Average Standard dev.	46.13 4.59	47 4.88	47 4.9
56–64	Reliable without restrictions	0 (0%)	2 (9%)	2 (5%)
47–55	Reliable with restrictions	6 (40%)	12 (55%)	18 (49%)
32–46	Non-informative	9 (60%)	8 (36%)	17 (46%)
Modified Eastlake's ranking scheme	Average Standard dev	1.5 0.74	2.05 0.87	1.81 0.89
Deficient SDS > 2 Q	In need of significant improvement	9 (60%)	6 (28%)	15 (38%)
Deficient SDS in 2 Q	In need of improvement	4 (27%)	8 (36%)	12 (32%)
Deficient SDS in 1 Q	Satisfactory	2 (13%)	8 (36%)	10 (30%)

examining Eastlake's criteria, since 28% of the studied datasheets were found as in need of significant improvement, 36% were in need of improvement, and 36% were deemed satisfactory.

Figure 3 depicts the average total scores of the eleven sections of the studied SDSs, grouped per revision period. The lowest ranked sections were the 14th (transport information) and the 12th (ecological information), for all datasheets of our sample, while the best scores were achieved for Sect. 7 (handling and storage), 5 (firefighting measures), and 2 (hazard identification).

Upon further evaluation of the 37 datasheets, and using the Eastlake et al. approach, it was discovered that questions Q2 and Q1 had the fewest positive responses (27%), whereas Q4 had the most (97%) (Fig. 4). These findings suggest that even though information about protective measures were provided, the vast majority of the datasheets were lacking specific nanomaterial information.

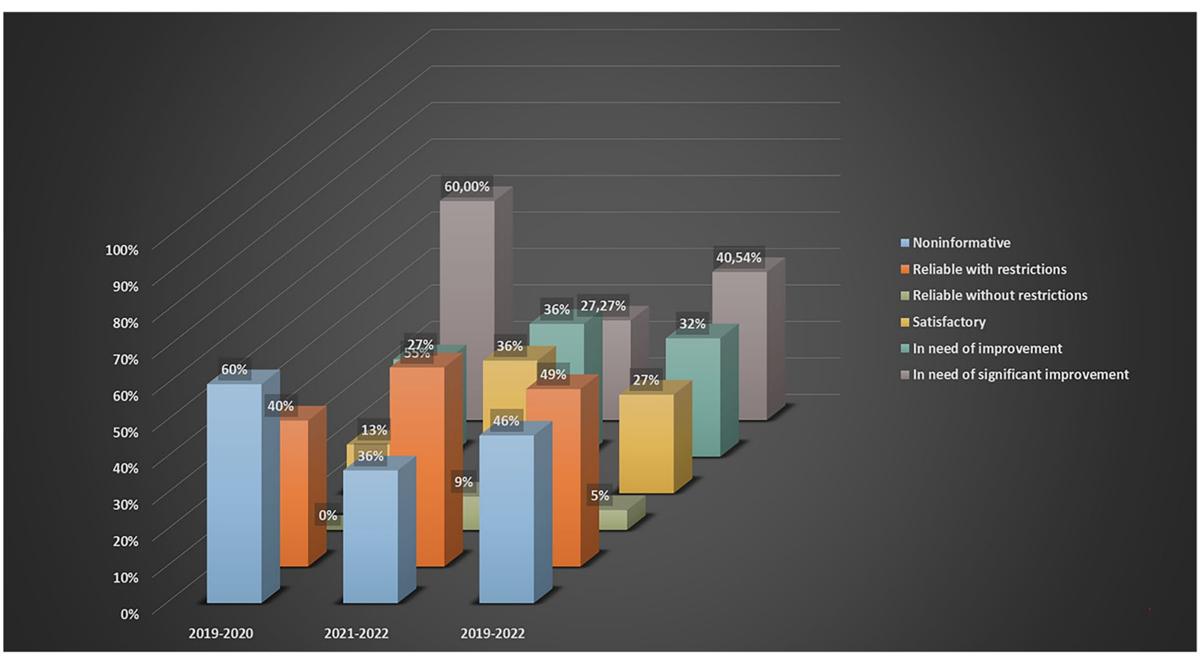

Fig. 2 Characterization of SDSs by date of last revision, using modified Hodson's dual ranking scheme

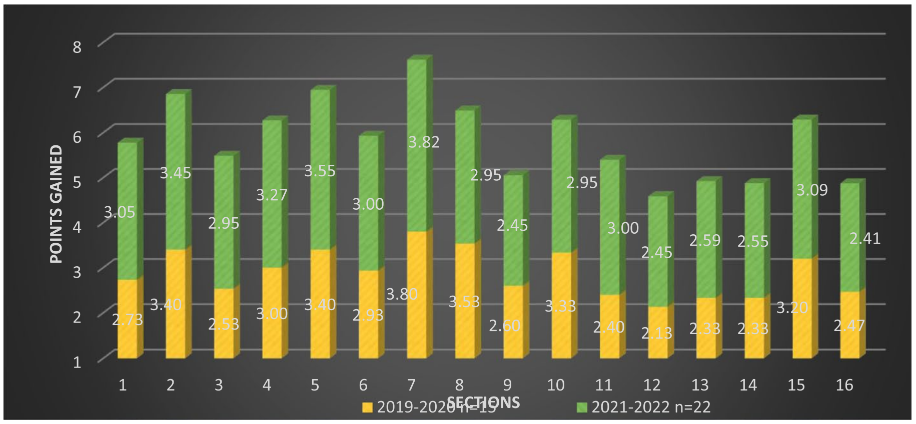

Fig. 3 Average total score by section in modified Hodson's ranking scheme (n = #SDS)

Technical specification sheets are becoming more popular, due to the need to document the physicochemical attributes particular to a material. From the datasheet sample, 41% were accompanied by a technical specification sheet, which is an important source of information regarding the material dimensions. Nevertheless, only 5 SDS out of 37 included size-related details, whereas 13 technical specification sheets supplementing them included the information. This resulted in an increase of the positive responses for the Eastlake et al. question 2 (state that material is in the nanoscale, numerically), moving from 14% (5/37) to 27% (10/37). None of the remaining details included in the technical specification sheets answered the model's questions.

The only notable difference when the technical specification sheet was included with the SDS was the information regarding the material size. This suggests that it might be mandatory to combine the details found on the datasheet with that on the TDS. A breakdown of the results for the Eastlake ranking system in terms of the inclusion of size data

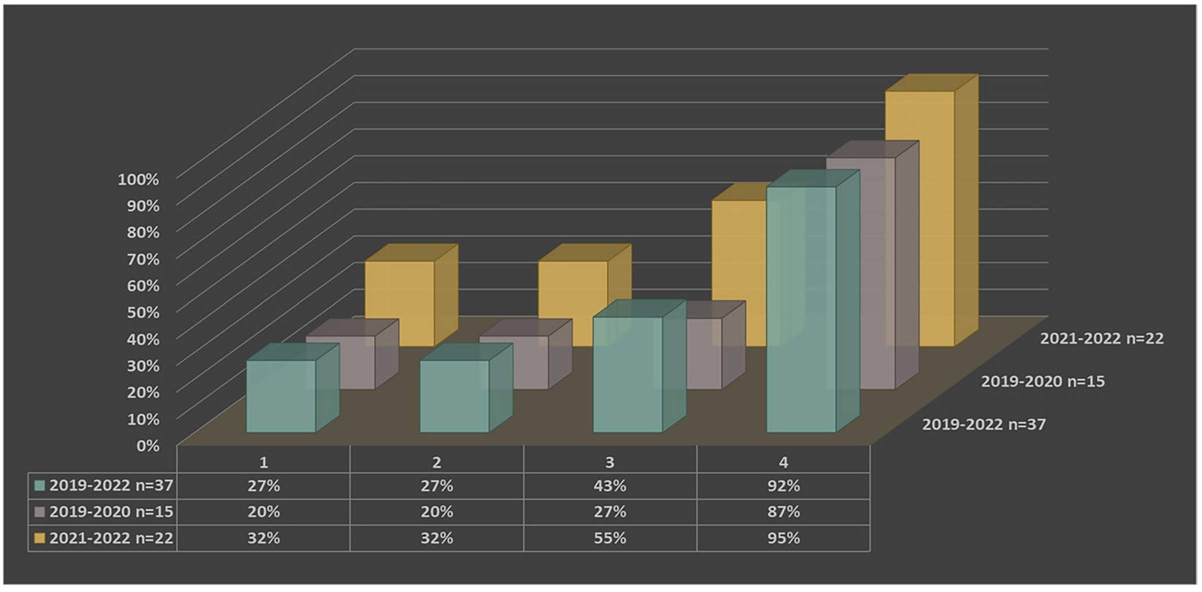

Fig. 4 Percentage of SDS's replied satisfactorily in each of Eastlake's questions (n = #SDS)

information via either the SDS or the TDS is presented in Table 4.

In order to know a material's status is to look at Sect. 15 (Fig. 5). In the United States, any chemical that is not listed on the Inventory is classified as a "new chemical substance." Moreover, apart from determining the "new" or "existing" status of a particular substance, the inventory also includes "flags" for existing chemical substances that are subject to manufacturing or usage restrictions. The US SDS for a specific material will change as the product moves from "newly prepared investigational materials" to a SNUR with consent order to a final SNUN (significant new use notification).

Only three percent refer that the material is not TSCA listed, which means the product is sold in small quantities to customers working in laboratory environments. The majority 84% do not include information. Fourteen percent have reached an intermediate degree of commercialization (TSCA listed) and for percental the SDS's there is a disclaimer.

Discussion

Although there were some missteps along the way, we are currently in the middle of a decade of discussions. Throughout this period, there have been numerous unfounded assumptions, underscoring the importance of conducting a comprehensive evaluation of Safety Data Sheets (SDS) to establish a sensible risk management approach. In order to chart a path forward, three key points have been identified:

A notable aspect is the recent discovery that the exploration of chemicals is fundamentally driven by cost considerations, which may result in findings that contradict science-based risk assessments. The physical synthesis process for large-scale nanocomposite fabrication is laborious, involving extended reaction times and expensive equipment [35]. Furthermore, chemical methods utilized in the process often involve hazardous and toxic chemicals, posing risks to the environment [36]. The cost of determining the chemical composition is estimated to be high, as it requires digestion of the material and may necessitate expertise and time-consuming sample preparation [37].

Table 4 Inclusion of size data via TDS or SDS per category of the studied SDS

	2019–2020	2021–2022	2019–2022
TDS founded	7/15	12/22	19/37
Size (data) provided via TDS	3/7	7/12	10/15
Size (data) provided via SDS	2/15	3/22	5/37

Second, is the underemphasis given to Sect. 15 which can provide details on the product status. It is crucial to verify if a chemical is listed on the inventory before commencing the manufacture (including importation) of a chemical substance. Although positive effects have been reported in Table 3 (49% reliable with restrictions), limited data are available regarding information on inventory lists. For instance, 84% not mentioned US-TSCA list and 73% did not mention EU-SVHC list. This might be due to the fact that SDS preparers may not always have the necessary resources to obtain available information [14].

Third, these points invite us to reconsider the unchartered Sects. 12–15. These sections can provide valuable information regarding the status of the product. At practical level, this mean that none of the SDSs are graphene products that have reached an intermediate degree of commercialization (a SNUR in US parlance) and therefore have not generated more information pertinent to that product and useful to production workers.

The vast majority of the studied SDSs did not precisely indicate the possible risks in an informative manner. Upon evaluating the selected datasheets, 5% were deemed to be of excellent quality and accurately informed about the potential risks of graphene-based materials. There were 49% datasheets described as reliable with restrictions, meaning that they included some general statements about the required protection measures without offering any specific details or any indication that the nanoscale dimensions of the material might pose a risk. Lastly, 46% of SDSs were found to require major improvements at communicating possible risks.

Both vendors and end-users should be able to comprehend the related regulations and ensure they are properly following them. It should be mandatory for manufacturers to revise their datasheets and corresponding labels as more information becomes available about the materials and their behavior [14]. The compilation and maintenance of datasheets is

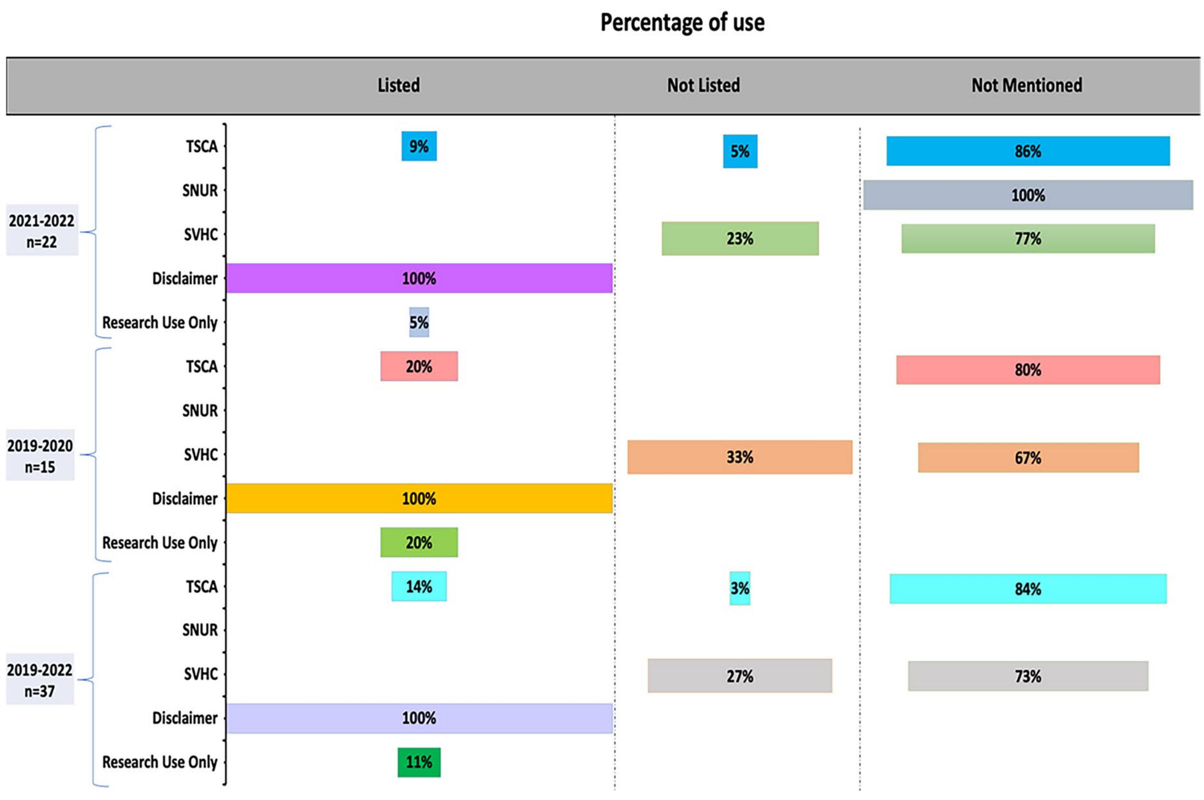

Fig. 5 Sect. 15 inventory lists

a significant expense [14], nevertheless, cannot be neglected. One of the positive outcomes is the verification that the majority of the datasheets offered advice about using protective equipment.

Kolchinski [38] delved on the problems related to incorrect or incomplete information on a safety datasheet. However, despite any quality control processes in effect, an error may happen during the publication of an SDS, which is a major concern and a potential safety hazard that should be taken into account.

Conclusions

This work proved that significant information is often omitted from SDSs. This assessment of graphene-based material SDS revealed that they are currently not yet fully reliable in terms of offering sufficient advice regarding the potential health and safety risks, and the appropriate handling and storage of nanoscale forms of the materials. It is concerning that based on our findings, multiple SDSs are considered to require major improvements; thus, the end users are not able to trust the information provided or interpret the limited information that might be included. The crux of the holistic evaluation approach is that all sections hold both economic and risk aspects. Section 15 can provide valuable information for material status (investigational vs. semi-commercial). The approach to form a holistic SDS profile provides an example with the promise of the field of knowledge. Moreover, one could realize that such an assessment will succeed by considering an SDS both from economic and safety side.

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Declarations

Conflict of interest The authors declare no competing interests.

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