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Watch your blind spot: how chemical regulations drive regrettable substitution

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Introduction: Chemical regulations seek to protect human health and the environment by controlling risks from hazardous chemicals and promoting their substitution with safe(r) alternatives. Regulatory frameworks such as the European Union/United Kingdon REACH (the registration, evaluation, authorisation and restriction of chemicals) and the Stockholm Convention (SC) are widely regarded as key mechanisms for driving such substitution. However, instances of regrettable substitution (RS), that is the replacement of hazardous chemicals with another that is equally harmful or the shifting of impacts from one concern to another raise questions about how effective these regulatory goals are being achieved. This article explores whether and how REACH and the SC may unintentionally exacerbate RS.

Methods: Drawing on empirical analysis of regulatory practice across three illustrative substance groups, per- and polyfluoroalkyl substances (PFAS), bisphenols and flame retardants, we use an explanatory sequential mixed methods approach which integrate online questionnaire with in-depth semi-structured interviews and document analysis.

Results: The study identifies nine interconnected sets of systemic and operational regulatory challenges that inadvertently exacerbate RS. The findings indicate that RS is exacerbated not by regulatory intent, but by features of regulatory design and implementation, including fragmented and uncertain regulatory landscapes, prioritisation of market access over substance-level evaluation, trade-offs between internal market functioning and risk management, persistent data availability and interpretation challenges, and limited regulatory capacity, enforcement, and information sharing.

Discussion: By clarifying how these challenges arise within REACH and the SC, this article contributes needed insights into why substitution outcomes may diverge from regulatory objectives and provide a basis for informed policy discussion aimed at strengthening chemical regulation to better prevent harmful substitution and support safe(r), more sustainable chemical production and use.

KEYWORDS

chemical regulations, chemical risk management, reach, reflexive thematic analysis (RTA), regrettable substitution, safe(r) chemical alternatives, Stockholm Convention

1 Introduction

Chemical regulations aim to protect human health and the environment, including facilitating the safe(r) replacement of the most hazardous chemicals. Hazardous substances classified and identified as posing particular concern such as those that are persistent, bioaccumulative, mobile, carcinogenic, mutagenic, reprotoxic or endocrine disrupting are recognised as contributing to adverse human health and environmental concerns and are a major contributor to global pollution (Brack et al., 2022; Sweetman, 2020). Addressing the risks posed by such substances is therefore a central objective of both regional and international regulatory frameworks.

The REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) regulation developed by the European Union (EU) and retained in the United Kingdom (United Kingdom REACH) represents the cornerstone of chemical management. EU REACH replaced over 40 legislative instruments when it entered into force in 2007 (Dosunmu et al., 2025; European Commission, 2018; Jones and Burns, 2024). Underpinned by the precautionary principle (European Commission, 2006), it aims to ensure a high level of protection of human health and the environment (REACH Article 1) (European Commission, 2006) while also enhancing EU chemical industry competitiveness. A key innovation of REACH is the concept of "No data, no market" (REACH Article 5), which shifts the responsibility for generating and submitting data on chemical hazards and risks to manufacturers and importers (European Commission, 2006). Greater access to information (developed under REACH) levels the market by enhancing transparency and harmonised approaches to chemical management (Stokes and Vaughan, 2013).

Registration is the starting point of REACH and requires companies placing chemicals on the market to generate and submit data on substance properties, uses and risks in order to demonstrate the safe use of substances, including consideration of effects on human health and the environment (European Commission, 2018; European Commission, 2006). Data requirements are linked to the manufactured or imported volume, with the most extensive information required for substances in the highest tonnage bands (>1,000 tonnes per year, t/y). Substances manufactured or imported below 1 t/y are currently exempt from the registration obligations of REACH. REACH registration has substantially expanded available knowledge on the properties, uses, and risks of many chemicals, facilitating improved risk management and control measures (ECHA, 2020a). Through the registration process, industry actors collaborate to jointly assess chemical risks via Substance Information Exchange Forums (SIEFs i.e., group formed by companies manufacturing or importing and registering the same substance), which facilitate data sharing and promote a more harmonised understanding of hazards and risk assessment approaches across companies. Registration results in the issuance of a registration number and access to the market (Dosunmu et al., 2025; Richter et al., 2021). Following registration, dossiers may be subject to compliance checks, test proposal examinations, and, where concerns remain, substance evaluation by authorities.

Hazard identification and communication under REACH are governed by the CLP Regulation (Classification, Labelling and Packaging of substances and mixtures Regulation (EC) No 1272/2008) (European Commission, 2023), which aligns EU classification with the United Nations' Globally Harmonised System (GHS). CLP establishes the criteria for identifying hazardous properties and communication of these hazards across the supply chain. CLP defines communication through pictograms, signal words, hazard statements, and precautionary statements. Classification under CLP provides the basis for subsequent risk management measures and informs regulatory decision-making across REACH processes.

Authorisation and restrictions are key risk management instruments under REACH and are widely recognised as drivers of substitution (ECHA, 2020b; Bergkamp and Herbatschek, 2014; ECHA, 2020d; European Commission, 2024; Ujaczki et al., 2022). Authorisation applies to substances of very high concern (SVHCs) listed in Annex XIV and requires companies to obtain permission to continue specific uses beyond a defined sunset date. SVHCs meet the criteria for carcinogenicity, mutagenicity or reprotoxicity (CMR), (very) persistent, (very) bioaccumulative and toxic (PBT/vPvB), (very) persistent and (very) mobile (PMT/vPvM) or have equivalent concern under REACH Article 57. Applications for authorisation must demonstrate either that risks are adequately controlled or that socioeconomic benefits outweigh the risks and that no suitable alternatives are available (European Commission, 2006; ECHA, 2020d; ECHA, 2021a; UK HSE, 2025a). As part of this process, applicants must carry out an Analysis of Alternatives (AoA), assessing the technical and functional suitability and availability of potential alternatives and outlining substitution plans (ECHA, 2020b). The AoA requires consideration of the potential unintended consequences of the alternatives used, recognising that the existence of alternatives does not automatically result in immediate substitution (European Commission, 2006; ECHA, 2021a). In addition, where the use involves more than one organisation, cooperation and communication across the supply chain is encouraged. Authorisation decisions are time limited and subject to review (ECHA, 2020a; ECHA, 2021a). In contrast, restriction functions as the safety net of REACH, enabling EU-wide conditions or bans where unacceptable risks cannot be adequately controlled by other measures (European Commission, 2018). When substances are restricted under Annex XVII, substitution is typically expected (ECHA, 2020c).

The Stockholm Convention (SC) on persistent organic pollutants (POPs) is a global treaty that addresses chemicals of international concern to protect human health and the environment from chemicals that persist, bioaccumulate, cause adverse effects (PBT) and undergo long-range environmental transport (LRET) (UNEP, 2024a). Since May 2004, the SC has expanded from 12 to 34 listed POPs, with Parties obliged to eliminate their production and use, exchange and communicate information on substitutes and monitor POPs in their jurisdictions (UNEP, 2024a; UNEP. TREATIES, 2001; UNEP, 2021). The SC is a "living treaty" allowing Parties to nominate new chemicals for inclusion on the SC's annexes as part of POP review committee (POPRC) processes (Sharkey et al., 2020; Wania and McLachlan, 2024). Criteria include thresholds for environmental half-life (persistence), bioaccumulation factor of >5,000 or octanol/water partitioning coefficient >5, documented evidence of human or environmental toxicity and evidence of LRET (through monitoring or modelled approaches) (Sharkey et al., 2020). The SC has significantly advanced

global chemical control of POPs, but concerns remain regarding the pace of listing, the nomination procedure, lack of capacity or technical knowledge among the Parties and issue with substitution of listed POPs (Wania and McLachlan, 2024; Scheringer et al., 2012; Muir and Howard, 2006; Sun et al., 2020; Diamond et al., 2015). Thus, highlighting the ongoing complexity of achieving safe and sustainable chemical substitution at both regional and global scales. The complexity of the management of chemicals is made more challenging by the volume of chemicals produced; a challenge called a 'wicked problem' due to the cross-agency management needed (Allen, 2013).

Over the years as a result of REACH and the SC, many chemicals are substituted with safe(r) alternatives but instances of substitution with unintentional consequences are reported; known as regrettable substitution (RS), the replacement of hazardous chemical with another that is equally harmful or the shifting of impacts from one concern to another. Maertens et al., (2021) considered lack of hazard data on the alternatives, trading one hazard endpoint for another, failure to consider exposure, lifecycle concerns and functional use as causes of RS. For instance, shifting from chemicals with ozone depletion to global warming potential, as the example of chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs) indicate (Mullin, 2002; Blum et al., 2019). The impact of CFCs on the stratosphere led to the implementation of the Montreal Protocol on ozone depleting chemicals (Mullin, 2002). Other examples are the substitutions of per- and poly-fluoroalkyl substances (PFAS), bisphenols and flame retardants (FRs) (Dosunmu et al., 2025; Blum et al., 2019; Reininger and Oehlmann, 2024; Yang and Yu, 2025; Cordner et al., 2025).

PFAS are a class of synthetic chemicals used in commercial applications since the 1940s and widespread use in consumer products from the 1950s (Gaines, 2023; Brase et al., 2021; Brendel et al., 2018). They found widespread use due to their unique properties which confer on them oil and water repellent and are used in applications among others, medical devices, consumer products, firefighting foams and food contact materials (Glüge et al., 2020). The unique properties that make them very useful also confer unwanted properties such as persistence, ability for a chemical to remain in the environment or biota for a long time without breaking down (Thiele et al., 2025). Examples are the legacy PFAS known as perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA). Due to their persistence nature and as a result of risk to humans and the environment, regional and global regulatory attention was drawn to them (Dosunmu et al., 2025; Thiele et al., 2025). For example, PFOA was added to Annex A and PFOS to Annex B of the SC UNEP (2024b) in addition to regional regulatory control such as that in Europe. This regulatory focus results in their substitution with alternatives such as perfluorohexanesulfonic acid (PFHxS) and perfluorobutanesulfonic acid (PFBS) among many others. These alternatives are also identified as SVHCs under REACH (Dosunmu et al., 2025; Hale et al., 2020) and PFHxS is included under Annex A of the SC without specific exemption (UNEP, 2026). The RS of PFOA is not an accidental outcome but a predictable result of systemic structural forces including corporate incentives, regulatory gaps, and institutional reticence that create persistent data and knowledge gaps enabling harmful chemical use (Dosunmu et al., 2025; Cordner et al., 2025).

Similar to PFAS is the substitution of bisphenols. Bisphenol A (BPA) is a high production volume chemical widely used in plastics, resins and in thermal paper; it's been substituted with close analogues such as BPS, BPF and BPZ and used instead for specific applications due to concerns about adverse effects, stricter regulatory controls and increased public awareness (Maertens et al., 2021; Reininger and Oehlmann, 2024; Yang and Yu, 2025; Trasande, 2017; Gys et al., 2020; Harnett et al., 2021; Wang et al., 2025; ECHA, 2020d). Under REACH, BPA is identified as a SVHC due to its endocrine disruption, carcinogenicity and reprotoxic properties (ECHA, 2017). In 2024, several bisphenols, including BPA, were banned in certain food contact materials and articles (European Union, 2024a). The alternatives are also identified as having similar properties to BPA due to their structural and potential functional similarity suggesting the need for a proactive and thorough screening of new chemicals before market access (Sweetman, , 2020; Yang and Yu, 2025; Trasande, 2017; Gys et al., 2020; Harnett et al., 2021; Wang et al., 2025; Scherer et al., 2014; Mesnage et al., 2017). For example, the replacement chemical, BPS is also identified as SVHC under REACH due to endocrine disruption and reprotoxic properties (ECHA, 2023a).

Unlike the substitutions of PFAS and BPA, which typically occur within the same chemical class, the substitution of FRs follows a more varied approach. In this case, alternatives may involve replacement chemicals from both similar and different chemical classes. To illustrate, substitutions of several halogenated FRs chemicals with phosphorus-based chemicals have occurred (Blum et al., 2019). FRs are class of chemicals that are used to meet fire safety regulations and added to articles to reduce the propagation of fire (Blum et al., 2019; Shaw et al., 2010; van der Veen and de Boer, 2012; De Boer and Stapleton, 2019). While fire safety regulations do not mandate the use of chemical FRs, their use has been widely adopted (Cowell et al., 2017); although many have argued for the need to evaluate the potential fire safety benefit against their impacts on humans and the environment (Shaw et al., 2010; De Boer and Stapleton, 2019). As a result of their widespread use in electronics, furniture, textiles and building materials, concerns around environmental contamination and adverse health impact exist, e.g., environmental persistence and human health toxicity (Shaw et al., 2010; De Boer and Stapleton, 2019; Cowell et al., 2017). The polybrominated diphenyl ethers (PBDEs) which are representative brominated FRs (BFRs) were used as three PBDE commercial mixtures (penta-, octa-, and deca-BDEs) since the 1970s (Sharkey et al., 2020; Blum et al., 2019; Shaw et al., 2010; Cowell et al., 2017; Abbasi et al., 2019). Due to environmental persistence and adverse health concerns such as carcinogenicity, penta/octa-BDEs and deca-BDE are subject to regulatory controls under REACH and are listed Under Annex A of the SC in 2009 and 2017 respectively (Sweetman, , 2020; Abbasi et al., 2019; UNEP, 2025a). This led to the substitution of PBDEs, an additive FR with other organohalogen FR e.g., decabromodiphenyl ethane and organophosphorus FRs e.g., tributyl phosphate and chlorinated alkyl phosphates e.g., tris(1,3-dichloro-2-propyl) phosphate (TDCP) and tris(1-chloropropyl) phosphate (TCPP) (Sweetman, , 2020; Blum et al., 2019; Shaw et al., 2010; van der Veen and de Boer, 2012; Cheng et al., 2023; Wang et al., 2020). Blum et al., (2019) compared the properties of organophosphate ester flame retardants (OPFRs) with those of PBDEs, and concluded that evidence from toxicity testing,

TABLE 1 Participants inclusion criteria.

S/N	Study inclusion criteria
i	Anyone that currently works or has previously worked in chemical regulation or chemical policy development
ii	Have experience with chemical regulation frameworks in a broader context such as EU/United Kingdom REACH, Stockholm Convention
iii	Have experience of chemical substitution, chemical alternatives assessment, alternatives assessment framework(s)
iv	Have experience of green chemistry, its principles and how it can be applied to chemical substitution and alternatives assessments

epidemiological studies, and risk assessments indicates health concerns at current exposure levels for both halogenated and nonhalogenated OPFRs. The authors emphasise that the findings highlight the need to develop safer alternatives using innovative approaches to maintain fire safety performance while reducing potential risks to human health and the environment. These examples exemplify the need to prevent continuous cases of RS through improved and effective regulatory approaches. In contrast to the substitutions of PFAS, bisphenols and FRs, the replacement of branched alkylbenzene sulfonates with linear alkylbenzene sulfonates (LAS) is widely regarded as a successful example of informed substitution. Introduced in 1964, LAS offered a readily biodegradable alternative, demonstrating how relatively small structural changes to a high-volume chemical can substantially reduce environmental impacts (Sweetman, , 2020). The regulatory actions on hazardous chemicals are welcomed and should be encouraged but RS makes such legislation only partially effective (Sharkey et al., 2020).

Chemical regulation is considered as a main driver for chemical substitution in addition to market factors such as consumer/customer demand and organisational policy (Sweetman, , 2020; ECHA, 2020b; Ujaczki et al., 2022; Coria et al., 2023; Slunge et al., 2022). For example, a survey by the ECHA found that 19% of companies mentioned restriction as the main driver for their substitution (ECHA, 2020b). The role of chemical regulations in influencing substitution of hazardous chemicals is reported in the literature (Sweetman, , 2020; Ujaczki et al., 2022; Coria et al., 2023), although little is known about how chemical regulations unknowingly drive RS.

This article explores whether, and how chemical regulation specifically the EU/United Kingdom REACH and the SC may inadvertently exacerbate RS. Drawing on the analysis of these two regulatory frameworks, the study aims to demonstrate how existing regulatory mechanisms can fall short of their stated objectives to promote substitution of the most harmful chemicals. By focusing on REACH and the SC, this article does not seek to generalise across all chemical regulatory regimes, but rather to contribute grounded insights that can inform debate and support practical improvements within comparable international and regional regulatory contexts.

2 Methodology

This study uses an explanatory sequential mixed methods design combining quantitative and qualitative data collection and analysis. The approach integrates three components; an online questionnaire, semi-structured in-depth interviews, and a review of regulatory, policy, and guidance documents. This design allows integrated qualitative and quantitative data collection, analysis and interpretation of the overall results (Asenahabi, 2019).

Participants who met the inclusion criteria outlined in Table 1 were recruited using purposeful sampling targeting individuals with professional experience of chemical regulation, risk management and chemical substitution. Key stakeholder groups including government (regulatory and policy), non-governmental organisations (NGOs), trade associations, consultancies, and businesses were included within the sample of participants. To broaden participation, a snowball technique was employed, whereby participants recommended relevant individuals within their professional networks who met the inclusion criteria. A brief description of the interview participants' experiences is provided in Supplementary Material (Supplementary Information 1).

2.1 Online survey

The online survey was designed and administered using Qualtrics (https://www.qualtrics.com) and was hosted over a 10-month period (October 2023-August 2024) to maximise opportunities for participation. The survey and by extension the study were actively promoted through multiple channels, including QR code, direct emailing, social media platforms (X and LinkedIn), publication in Chemistry World (Chemistry World, 2024), conference attendance, e.g., the 2023 Fluoro conference on PFAS at Idstein Germany, the 2024 Society of Environmental Toxicology and Chemistry (SETAC) in Seville Europe Annual Meeting and presentation at relevant meetings such as the United Kingdom Hazardous Substances Advisory Committee (HSAC).

Participation was conducted anonymously, although survey respondents could voluntarily provide contact details if they wished to participate in the interviews. The survey comprised a combination of multiple-choice questions, Likert scale ratings, and free text responses, and was designed to capture stakeholder views on current regulatory approaches related to the substitution of hazardous chemicals. Of the 87 individuals who participated in the survey, 52 completed responses were retained for analysis after exclusions for non-consent or incomplete submissions. The response and completion rates are consistent with surveys targeting specialised professional populations (Coria et al., 2023; Kost and Correa da Rosa, 2018; Wu et al., 2022). Survey data were analysed using descriptive statistics (e.g., frequency distribution) in Microsoft Excel to generate an overview of response patterns.

TABLE 2 Demographic information for survey and interview participants; where, Other = Professional body.

Participant sector	Survey (N = 52)		Interview (N = 31)	
	Frequency	Percentage (%)	Frequency	Percentage (%)*
Industry	15	29%	9	29%
Government (policy and regulators)	13	25%	7	23%
Consultancy	10	19%	6	19%
Academia	7	13%	5	16%
Association	4	8%	1	3%
NGO	2	4%	2	6%
Other	1	2%	1	3%

*Total may not exactly equal 100% due to rounding up.

2.2 Interviews and document collection

The qualitative aspect of the study consisted of semi-structured interviews, (N = 31), free text survey responses and review of relevant regulatory, policy, and guidance documents (N = 17) with a particular focus on REACH and the SC. Semi-structured interviews were conducted based on an interview guide (see Supplementary Information 2) using Microsoft Teams between November 2024 and March 2025, with interviews typically lasting between one to 2 h. An interview protocol following the suggested format of Boyce and Neale (2006) was prepared and used as a template to contact and arrange the interviews with participants (see Supplementary Information 3). Prior to the interview, interviewees received information about the study and provided informed consent. All data were anonymised before analysis.

2.3 Qualitative analysis

Interview transcripts, free text survey responses, along with documents were analysed using reflexive thematic analysis (RTA) as developed by Braun and Clarke (Braun and Clarke, 2019; Braun et al., 2006; Braun and Clarke, 2022). The analysis followed an iterative and primarily inductive approach using open coding to capture meanings emerging from the data (Braun and Clarke, 2019; Lincoln and Guba, 1985). NVivo (version 15.2.2, https://lumivero.com/) was used to manage and organise the qualitative data. However, all interpretation, coding, and theme development remained researcher driven. The analysis followed Braun and Clarke's (2019; 2022) six phase framework, encompassing familiarisation with the data starting from the preparation of the interview summary document, see Supplementary Information 4, systematic coding, theme development, review and refinement of themes, definition and naming of themes, and analytical writing. See Supplementary Information 5 for further details on the qualitative analysis approach, documents analysed and example codes and quotations.

The epistemological orientation of RTA is central to how the findings are produced. Themes are not treated as objective properties residing within the dataset, but as interpretive, researcher-generated outputs, developed through iterative and reflexive engagement with the data. This approach prioritises depth, meaning-making, and theoretical sensitivity over reproducibility in the positivist sense (Braun and Clarke, 2022). Accordingly, the analysis should be read as a situated and theoretically informed interpretation, offering nuanced insight into regulatory (particularly REACH and SC) influence on RS rather than exhaustive or universally generalisable conclusions.

2.4 Research ethics

The proposal for this research was reviewed and approved by the Lancaster University Faculty of Science and Technology Research Ethics Committee (ref. FST-2023-3427-RECR-3) before data collection.

3 Results

3.1 Survey findings

Participant demographics are presented in Table 2 and Figure 1A for survey and Figure 1B for interview respondents. The breakdown shows an even representation across the demographics, participants from industry covers chemical, agrochemical, pharmaceutical and consumer good companies.

Responses to the Likert-scale and multiple-choice questions are presented in Tables 3-6 and Figures 2A–D.

3.2 Qualitative analysis findings

The thematic findings illustrating systemic and operational regulatory challenges within REACH and the SC is presented in Figure 3. The findings show how systemic challenges shape the regulatory context within which operational challenges arise, collectively contributing to the exacerbation of RS. Example codes and quotations are presented in Figure 4.

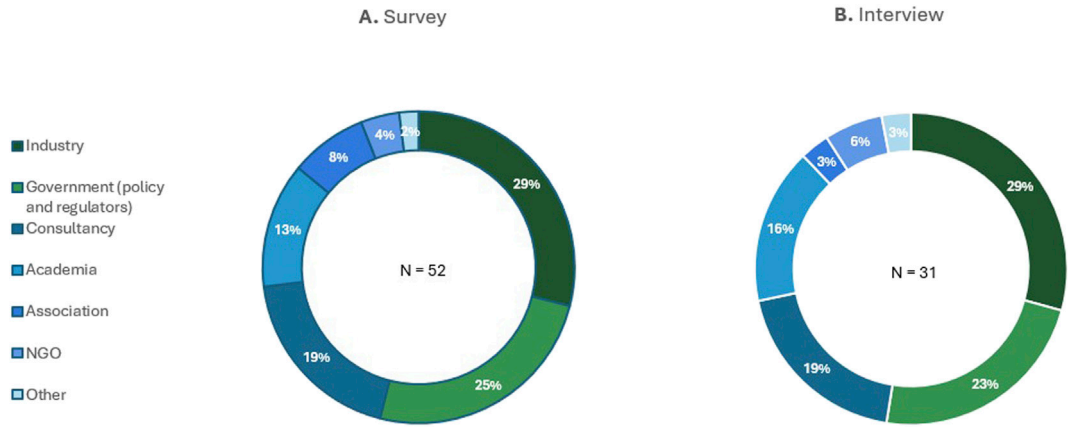

FIGURE 1
Demographic information **(A)** survey participants **(B)** interview participants.

TABLE 3 **Summary table for responses from all sectors to the statement 'chemical regulation unintentionally exacerbates RS'.**

Level of agreement	Frequency	Percentage	Combining disagree/agree	
Strongly disagree	2	5%		
Somewhat disagree	8	19%	23%	Disagree/strongly disagree
Neither agree nor disagree	13	30%	30%	Neither agree nor disagree
Somewhat agree	12	28%	47%	Agree/Strongly agree
Strongly agree	8	19%		
Total	43			

TABLE 4 **Summary table for responses from different sectors to the statement 'chemical regulation unintentionally exacerbates RS'.**

Participant sector	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree	Grand total
Academia		20%	40%		40%	5
Association		50%	50%			2
Business - industry		8%	42%	17%	33%	12
Consultancy	12.5%	25%	50%	12.5%		8
Government (policy and regulator)	8%	15%	8%	69%		13
NGO		50%			50%	2
Other					100%	1
Grand total	2	8	13	12	8	43

4 Discussions

4.1 Descriptive statistics (survey)

Our survey data show that respondents hold a varied view regarding the extent to which they agree with the statement '*chemical regulations unintentionally exacerbate RS*'. This varied view on the Likert scale may be attributed to professional experience, perceptions and difference in perspectives of what constitutes RS and the understanding of regulatory contribution to this. For example, we found that about 13% of respondents from consultancy (N = 8), 50% from industry (N = 12) and 70% from the Government (N = 13) agreed with the statement (i.e., somewhat or strongly) that

TABLE 5 Summary table for responses from all sectors to the statement 'data availability is important when making decisions on alternatives assessment'.

Level of agreement	Frequency	Percentage
Strongly disagree	0	0%
Somewhat disagree	1	2%
Neither agree nor disagree	1	2%
Somewhat agree	14	34%
Strongly agree	25	61%
Total	41	

chemical regulations unwittingly exacerbate RS (Figure 2A), when the responses are considered across all participants, N = 43, about 50% agreed and 30% has a neutral view (Figure 2B). Contrarily, respondents overwhelmingly agreed, (over three quarters, 95%, N = 41) that data availability plays a significant role in decision making when performing alternatives assessment and substituting hazardous chemicals (Figure 2C). This agreement indicates the importance of availability of reliable and useable data when managing the risks from such chemicals. More so, we asked participants to select the primary reason for conducting alternatives assessment, the majority (85%, N = 34) of the respondents select chemical regulation as the major driver for substitution

TABLE 6 Summary table for responses from different sectors showing primary reason for performing substitution/alternatives assessment.

Participant sector	Regulatory requirements	Research	Customer/Consumer demands	Grand total
Academia	60%	40%		5
Association	100%			2
Business - industry	91%		9%	11
Consultancy	100%			8
Government (policy and regulator)	86%	14%		7
NGO		100%		1
Grand total	29	4	1	34

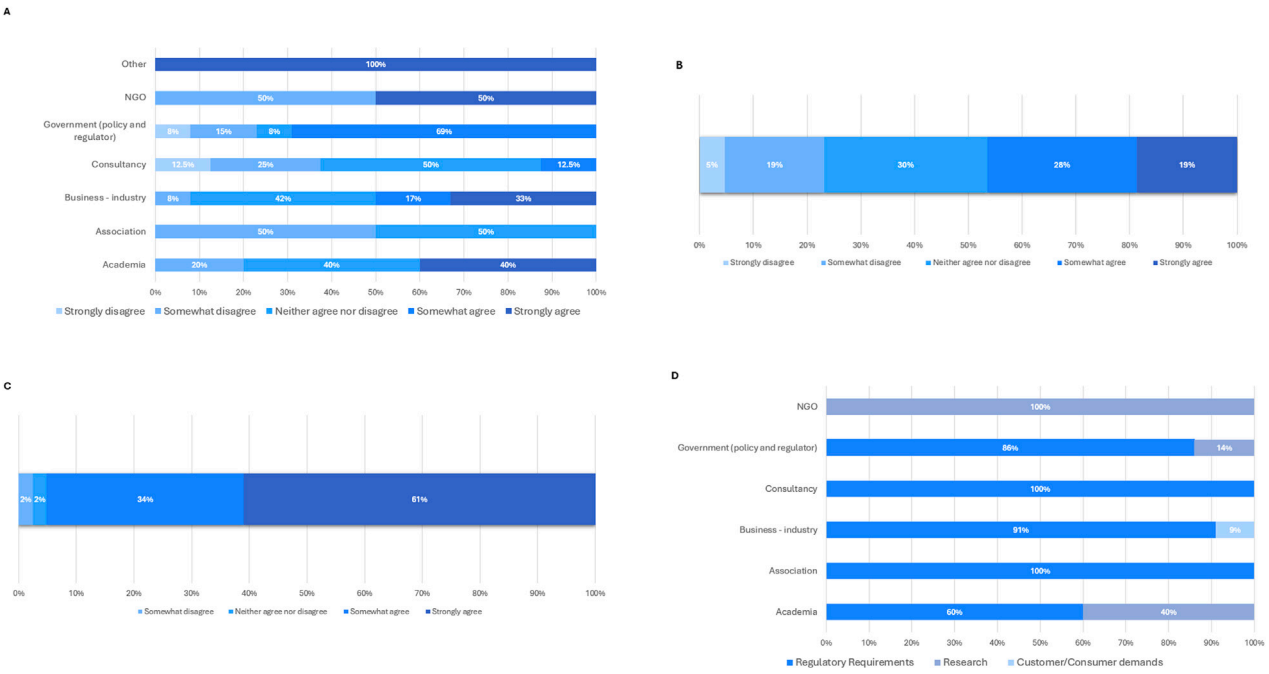

FIGURE 2
Survey findings: **(A)** responses from different sectors to the statement chemical regulation unwittingly exacerbates regrettable substitution **(B)** responses from all sectors to the statement chemical regulation unwittingly exacerbates regrettable substitution **(C)** responses to the statement data availability plays an important role in decision making during alternatives assessment **(D)** Responses to multiple choice question on the primary reason for performing substitution/alternatives assessment.

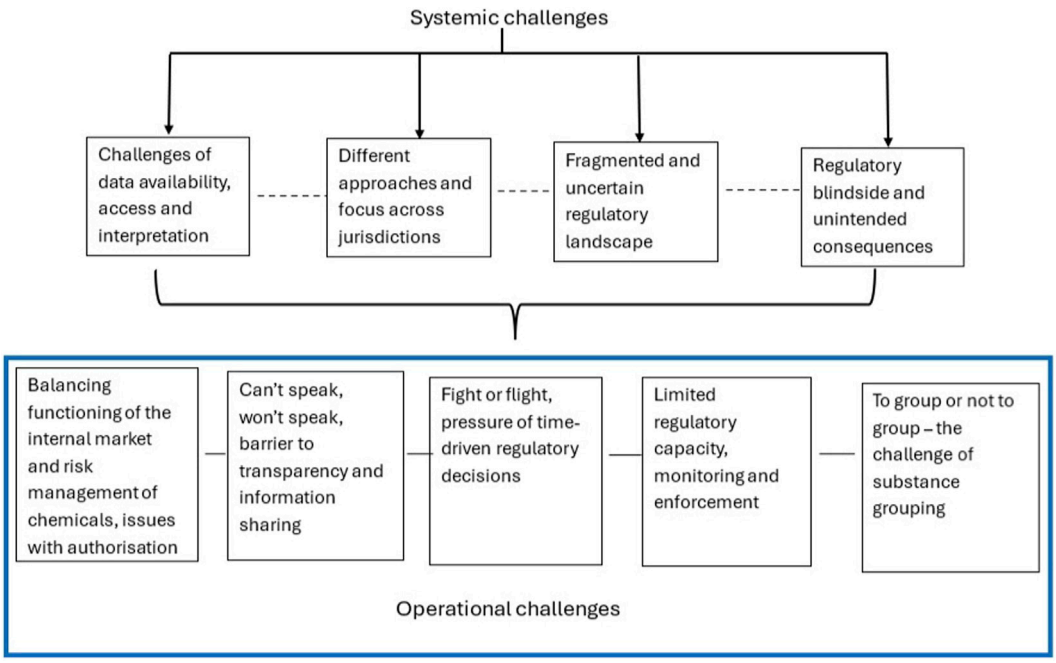

FIGURE 3
Thematic findings showing how REACH and SC exacerbate RS.

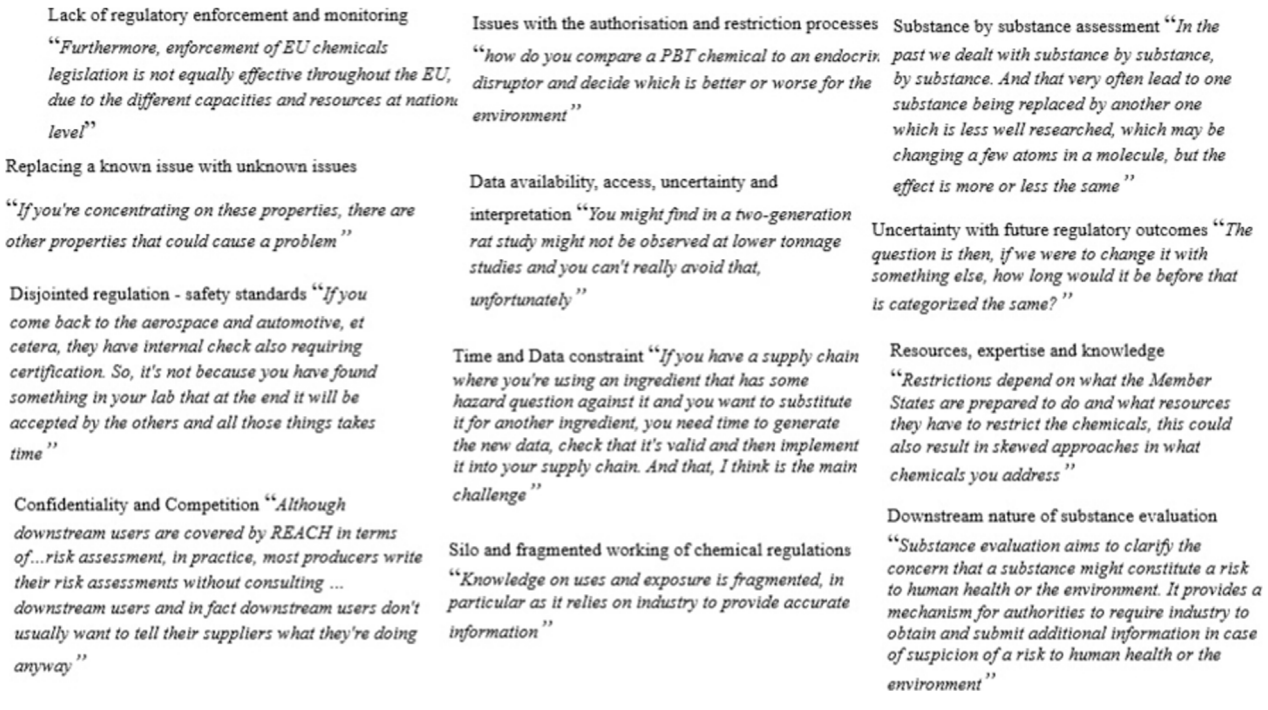

FIGURE 4
Example codes and quotations, see Supplementary Information 5 for additional codes and quotations.

(Figure 2D). The need for substitution is driven by chemical regulations, consumer demand and organisation policy. As regulatory requirements tighten or change, chemicals are substituted and replaced with alternatives (Ujaczki et al., 2022).

4.2 Thematic findings

This section presents the nine interconnected themes constructed through RTA (Figure 3). Our findings reveal both

systemic and operational challenges in the development, control, and management of hazardous chemicals, as well as in the efforts to encourage their substitution. Whilst the study draws on participants from a range of sectors, its analytical focus was deliberately confined to how regulatory design and implementation may shape, and at times exacerbate RS. Other drivers of RS such as customer demand (Figure 2D) or agnotological practices are not explicitly examined (Richter et al., 2021; Pinto and Leuschner, 2026). This reflects purposeful scoping, allowing the study to generate focused evidence based on the role of regulation in RS.

Methodologically, the study relies on voluntary participation and modest sample size, which introduces the potential for self-selection and response bias. However, within a qualitative research paradigm, and particularly RTA, sample adequacy is assessed in terms of analytical depth and diversity of perspectives rather than statistical representativeness. The aim is not probabilistic generalisation but the development of conceptually robust and interpretive insights. The inclusion of participants from multiple sectors, alongside documentary and policy analysis, supports triangulation and strengthens interpretive credibility.

The geographic focus on actors engaged with EU/United Kingdom REACH and the SC situates the findings within a specific regulatory and socio-political context. Accordingly, the findings should be read as a situated and theoretically informed interpretation of how these frameworks influence RS, rather than as universally generalisable conclusions.

4.2.1 Systemic regulatory challenges

4.2.1.1 Challenges of data availability, access and interpretation

REACH data requirements are based on market volume according to Article 12. Substances manufactured or imported at higher tonnages must meet more extensive data requirements, "*. . .the registration requirement is therefore triggered by the volume of the substance manufactured or imported . . . The volume . . . will also determine the information to be submitted in the registration dossier . . .* " (ECHA, 2021b). This tiered system means that for low tonnage substances e.g., 1-10 t/y, 10-100 t/y, essential chronic toxicity data may not be available when deciding on substitution, as these tests are expensive and require specialised knowledge (Dosunmu et al., 2025; Maertens et al., 2021; Yang and Yu, 2025). Tonnage is used as a proxy for exposure (Coria, 2018), because exposure increases with market volume. However, effective substitution decisions depend on data availability as the survey responses show (Figure 2C). When required data are lacking, significant knowledge gaps arise, making substitution decisions difficult and challenging. As one participant from industry explained, "*. . .the more you make of a substance, the more data you have to present . . . if you make more than 1,000 tonnes . . . you have to put in a lot more safety data . . . below 100 tonnes, it's significantly less . . . So, what can happen is a company would use an alternative . . . of lower volume . . . and consequently there is less data . . . the volume of that alternative increases . . . authorities then find out . . . there is a problem . . .* ". A notable example is dichloromethane, previously used in paint strippers. Its substitute, n-propyl bromide, appeared suitable when produced at a low tonnage but was later found to be more hazardous when higher tier studies became mandatory, ultimately leading to its SVHC listing due to its reprotoxic properties (ECHA CHEM, 2012). Thus, decision making for low tonnage substances is disproportionately constrained by limited data. While lowering data thresholds could enhance safety, it may also hinder innovation, especially for small businesses, "*. . .if we have the same data requirements for 1 to 10 tonnes as 1,000 tonnes . . . it will stop innovation overnight . . . But it is a risk because an unexpected harm . . . might not be observed at lower tonnage studies . . .* participant from Industry". Similar patterns were observed in the substitutions of PBDEs with TCPP and TDCP, although initially seen as environmentally preferable, some were later found to be carcinogenic following higher-tier studies (Blum et al., 2019), "*. . .the replacement, the chlorinated alkyl phosphates were environmentally very acceptable . . . turned out that they're carcinogenic . . . not all of them . . .* Participant from Consultancy".

Under REACH, data should be generated using standardised Organisation for Economic Co-operation and Development (OECD[1]) test methods or EU test methods (Regulation (EC) No. 440/2008[2]) (European Union, 2024b). These methods ensure consistency and reliability across studies. However, academic research is an important source but often excluded from regulatory assessments due to methodological differences. For example, only 21 out of 142 reviewed studies were deemed suitable for BPA hazard assessment by the Food and Drug Administration (Maertens et al., 2021). Academic studies often diverge from regulatory requirements in design, reporting standards, and reproducibility (Jones et al., 2025; OECD, 2025). In addition, current test methods heavily rely on animal studies, which are costly, time-consuming, and low throughput, making them impractical for the volume of chemicals requiring assessment (Yang and Yu, 2025). To address these issues, the OECD recently published a guidance aimed at improving regulatory usability of non-standard academic data, bridging the gaps between research and regulatory frameworks (OECD, 2025).

Interpretation of data often varies across stakeholders, creating uncertainty and delaying agreement on risk management. As one participant from industry explained, "*. . .you have to be sure that the signs on the horizon are true and not conflicting. You cannot navigate with a mirage, and you cannot really navigate if you've got two different interpretations of data . . .* ". Divergent interpretations arise due to differing expertise, borderline study results, varied evaluation criteria or differences in study quality. This uncertainty emphasises the need for transparent and consistent risk assessment (Ingre-Khans et al., 2016), highlighting the influence of expert judgment and potential bias in chemical evaluation (Beronius et al., 2010; Rohr and Mccoy, 2010). Bias may also emerge from the data generation process itself. REACH requires manufacturers and importers to generate and propose classifications for their substances. While this system addresses pre-REACH data gaps (European Commission, 2001), it raises concerns about conflicts of interest, "*. . .there is a negotiation in how data are being presented in the test reports . . .*

1 OECD Guidelines for the Testing of Chemicals. https://www.oecd.org/en/topics/sub-issues/testing-of-chemicals/test-guidelines.html

2 https://www.legislation.gov.uk/eur/2008/440/contents

that's like an inbuilt bias based on a conflict of interest . . . very problematic . . . Participant from Academia". This is more important since the information submitted to regulatory agencies forms the basis for risk management and control. While regulatory agencies can request further information (REACH Article 36 (1)), evaluating these data requires substantial resources and time (Ingre-Khans et al., 2016).

Beyond data availability, current test methods remain limited in scope. For example, carcinogenicity testing is not routinely required under REACH and is only triggered when concerns arise. Even then, securing contract research organisation capacity and interpreting results can be challenging. Moreover, some hazards such as endocrine disruption may not be captured adequately by existing test requirements (Maertens et al., 2021), requiring regulatory agencies to perform extensive substance evaluation to clarify concerns. One participant from government noted regarding carcinogenicity, "*. . .you can't identify this chemical as a carcinogen based on the data requirements for even 1,000 tonnes . . . we'd have to go for . . . far-reaching substance evaluation . . . but it takes years . . .* ". Therefore, regardless of the regulatory framework, REACH or SC, data availability remains fundamental. Robust hazard knowledge, effective risk management and substitution depend on reliable, high-quality data.

4.2.1.2 Different approaches and focus across jurisdictions

Safety standards in sectors such as fire protection, automotive manufacturing, and aviation are designed to prevent accidents, protect human life, and ensure reliable product performance. Chemicals are central to meeting these objectives. FRs enable compliance with flammability requirements, PFAS-based materials provide heat resistance, water repellence, specialised additives support the functional and mechanical integrity of vehicles and aircraft. However, chemicals that are essential for meeting strict safety and performance requirements often raise concerns for human health and the environment. This tension creates an imbalance between performance-based safety standards and hazard- or risk-based chemical regulations. A substance may be important for fire or industrial safety yet simultaneously face regulatory action due to persistence or toxicity or other hazardous properties. Conversely, safer-seeming alternatives may fail to meet the performance criteria required for sector specific certifications, ". . .in *aerospace and automotive . . . they have internal checks also requiring certification . . . it's not because you have found something in your laboratory that . . . it will be accepted . . . and all those things takes time . . .* Participant from Association". Therefore, when performance demands are high, manufacturers often rely on structurally similar drop-in substitutes, increasing the risk of RS (ECHA, 2020a), "*. . .your alternative must work as well or better . . . for automotive you might be talking three to 5 years to qualify an alternative . . . unless the law steps in . . . they will not accept any deterioration in performance . . .* Participation from Industry".

Long, complex validation and approval processes can also delay the adoption of safe(r) substitutes (Ujaczki et al., 2022). For example, chromium (VI), (Cr(VI)) used widely for corrosion resistance and aesthetics generated a high number of authorisation applications, creating significant administrative burden. The EC now plans to restrict Cr(VI) given the strain the authorisation workload placed on regulating other hazardous chemicals (ECHA, 2023b). Although upstream applications were made to streamline the process by covering multiple downstream users, increasing demands for granular data made this unmanageable "*. . .they're asking more or less each detail for each company . . . which is impossible . . . each downstream user started to apply by themselves . . . they have been overloaded by dossier . . .* Participant from Association". Regulatory uncertainty and limited technically viable alternatives further constrain innovation, making it difficult to identify substitutes that meet both safety and regulatory requirements. Thus, substitution in safety-critical sectors remains a complex balancing act between protecting consumers, regulatory compliance, and maintaining product integrity. Where this is the case, the concept of essential use becomes important (Figuière et al., 2023). A participant from Government explained "*. . .this is . . . an area where we have developed a new concept, it's called the essential use concept . . . the idea is that where uses are important for society, we accept that continued use might be necessary. Whereas when users are more kind of luxury uses . . . and here we are saying there is no justification for incurring any risk for workers in that case . . .* ".

Regulatory divergence across frameworks intensifies this issue. Under REACH, substitution decisions follow a risk-based approach incorporating exposure and socioeconomic considerations, although some argued EU chemical management is increasingly hazard focused (Ujaczki et al., 2022). By contrast, global frameworks such as the SC use hazard-based criteria targeting elimination or reduction of POPs. This can lead to substitution choices that comply with one system but remain problematic under another, "*. . .if . . . you want to sell into the rest of the United Kingdom and into Europe and preferably America too . . . you have to meet the laws . . . also in Europe and America . . . anything that happens in EU law will inevitably affect industry in the UK . . .* Participant from Industry". Hazard information is crucial for identifying chemicals of concern, allows consistent regulatory approaches especially when exposure data is incomplete. However, focusing solely on hazard can overlook potential exposure pathways and insufficiently characterised or understated exposure can lead to RS (Maertens et al., 2021). For instance, BFRs were replaced with OPFRs under the assumption that reduced persistent will lower exposure, yet subsequent evidence showed widespread and significant OPFR exposure (Maertens et al., 2021; Blum et al., 2019).

Chemical use, trading and concerns cut across boundaries, hence differences in regional regulatory requirements further compound the problem, "*. . .the last thing the industry want is . . . a substance classified differently in different regions . . . it would cause . . . problems to supply chains . . .* Participant from Consultancy". Different classifications, permitted uses, and restrictions mean companies may adopt substitutes that satisfy immediate requirements yet prove hazardous in the long-term (ECHA, 2020c). Regional regulatory priorities also differ, what one jurisdiction considers a chemical of concern may not be treated similarly elsewhere (Ujaczki et al., 2022). A comparative analysis of substitution principles across EU regulations for pesticides, biocides and industrial chemicals found slow implementation and alternatives lacking sufficient hazard data, leading to RS (Slunge et al., 2023). These issues reflect the challenges posed by fragmented regulatory systems, where differing terminology and evidentiary requirements complicate global compliance. For example, chemicals with LRET potential require nomination before inclusion under the

SC, delaying global control. Together, these dynamics undermine efforts to achieve safe(r), sustainable chemical solutions and emphasise the need for greater regulatory coherence across regions and standards.

4.2.1.3 Fragmented and uncertain regulatory landscape

Chemical risk management is typically based on use categories such as agrochemicals, biocides, or pharmaceuticals resulting in siloed and fragmented regulatory approaches. Failure of regulatory frameworks to communicate can lead to increased exposure, as indicated by the example of PFAS (Dosunmu et al., 2025). One participant from consultancy explained, "*. . .some substances are regulated not just under REACH, but also under the Food Standards Agency, EFSA . . . You might have many polymers and monomers . . . under REACH and . . . EFSA . . . and then . . . cosmetics . . . What it was really about was . . . you might be exposed . . . from two or three different regulatory regimes. And if those . . . were not talking to each other, you could end up with some rather strange conclusions . . .* ".

Siloed regulatory practice means knowledge on chemicals is fragmented across frameworks, with agencies focusing only on their area, be it cosmetics, industrial chemicals, or agrochemicals. Such fragmentation can create inconsistencies and gaps in chemical oversight (Dosunmu et al., 2025) and fails to adequately protect against the multitude of chemical exposures (Topping et al., 2020; van Dijk et al., 2021). In the EU CSS, it was highlighted that "*. . .knowledge on uses and exposure is fragmented . . . The sheer number of chemicals on the market represents an immense knowledge challenge . . .* ". For example, current Safe and Sustainable by Design (SSbD) framework primarily focused on industrial chemicals, reflecting historical sector-based divisions (Ellis and Dosunmu, 2025). As one participant from government noted, "*. . .if SSbD is a vehicle for green chemistry . . . we will have to look at a number of regulations, so REACH is just a minor part . . .* ".

Fragmentation also appears in chemical safety assessment (CSA). Under REACH, manufacturers and importers demonstrate safe use upstream based on assumed conditions that may differ substantially from downstream realities. When chemicals are used differently or more extensively than anticipated, unintended emissions may arise (Dosunmu et al., 2025). Although downstream users may prepare their own CSA, they are not required to submit them to the Agency (REACH Article 37 (7)). This illustrates how fragmented approaches addressing only parts of the supply chain miss critical risks. Given that chemicals move across sectors and applications, such siloing contributes to ongoing exposure issues, reflected in the recent restriction of BPA and other bisphenols in food contact materials (European Union, 2024a).

REACH aims to encourage the substitution of the most hazardous chemicals with safe(r) alternatives. However, substitution decisions are challenging, multi-faceted, and complex, influenced by factors such as data availability, business needs, and regulatory actions (Blum et al., 2019). While substitution is widely recognised as a central principle of modern chemical regulation including REACH and the SC (Sweetman, , 2020; Ayad et al., 2025; ECHA, 2025a; Syeda et al., 2022), uncertainty about future regulatory outcomes can discourage organisations from transitioning away from SVHCs. One participant from industry explains, "*. . .if we were to change it with something else, how long would it be before that is categorised the same? . . .* " RS reflects the difficulty policymakers face in balancing well-characterised risks with uncertainties surrounding newer alternatives (Scherer et al., 2014). Conversely, a purely hazard-based system with little consideration of exposure can also hinder innovation, since exposure control remains an important regulatory lever (Ujaczki et al., 2022).

This uncertainty is heightened by evolving regulatory requirements and goals, which means a chemical considered safe based on current hazard data may come under scrutiny as new evidence emerges. While this may be necessary since knowledge on chemicals changes with scientific understanding, its impact on substitution decisions should not be overlooked. "*. . .What industry definitely needs is . . . the certainty that if they (substitute), . . .they can actually do business with the process that they have developed . . . by having a sort of a plan . . . you can create that certainty, because you require industry to work towards a goal and if somebody identifies an alternative, there is sufficient time to move to that. So, there shouldn't be, let's say in the middle of the process sudden change to say OK you have to substitute now, but there needs to be a period where industry can substitute overtime . . .* Participant from Government". When regulatory goals shift or remain unclear, businesses may default to low-risk, quick substitutions, even when these later prove regrettable. As another participant highlighted, "*. . .uncertainty has been a major stumbling block for many businesses, the ones that are currently using the substances that we would hope they would substitute, but also the ones that offer the alternatives . . .* Participant from Government". A transparent, predictable regulatory system is therefore essential to maintain confidence while achieving the core purpose of protecting human health and the environment.

Regulatory complexity and ambiguity further exacerbate the risk of RS, especially for small and medium sized companies (SMEs) that lack the capacity to interpret extensive regulatory requirements, "*. . .the regulation and the guidance . . . comes to about 13,000 pages . . . smaller organisations can't even think about that let alone understand it . . .* Participant from Consultancy". Complex regulatory landscapes increase the likelihood that alternatives will be selected without a full understanding of their hazard profiles or long-term regulatory implications. SMEs are often particularly vulnerable, "*. . .regulatory resource in SMEs is very difficult to come by . . . people . . . are expected to pick it up . . . the regulatory landscape is so complex and intertwined . . .* Participant from Industry". When regulation becomes too complex to navigate, it increases organisational burden and may discourage substitution altogether. Firms may prioritise compliance over innovation, choosing alternatives that meet immediate regulatory needs rather than those that are genuinely safe(r). Increased complexity also raises costs, further limiting the ability of smaller companies to invest in safe(r) substitution. Together, regulatory uncertainty, complexity, and ambiguity create an environment where RS becomes more likely, contrary to regulatory intentions.

4.2.1.4 Regulatory blindside and unintended consequences

Registration of chemicals forms the foundation of data generation under REACH by requiring submission of hazards and exposure data prior to market entry. According to REACH

Article 5 "*No data, no market*" (European Commission, 2006); registrants must demonstrate safe use of a chemical under given conditions with the evaluation system built in as a check and balance mechanism. REACH was widely regarded as a turning point, "*. . .a paradigm changes when REACH came into force, we got this premarketing obligation to register everything but from one tonne . . .* Participant from Government". Registration gives a "*. . .very strong incentive to provide information, because otherwise the chemical is not allowed to be on the market, you do not get a registration number . . .* Participant from Government". However, the issue with registration-first approach is that once a chemical is registered, it gains unrestricted market access. As chemicals are subsequently used in varied applications, registration alone may not actively encourage substitution unless the substance is later evaluated as an SVHC and subject to regulatory restriction or ban. As noted by one academic participant, "*. . .registration itself I don't think in my view, it doesn't contribute to substitution. This registration is like a black and white thing, is either you're registered, you're fine, your chemical safety report, or your risk assessments and hazard assessment is OK. So, then there are no real incentives for substituting . . .* ". For example, De Boer and Stapleton (2019) found the production of potentially hazardous and environmentally unfriendly FRs continues despite the availability of alternatives. The issuance of a registration number signals successful registration and full market access (Dosunmu et al., 2025; ECHA, 2021b), creating a psychological perception of safety. However, this assumption is only as strong as the underlying data and quality of the assessment. In contrast to REACH, other regulatory regimes impose periodic reassessment. For example, pesticides require regular review, reauthorisation and reapproval every ten or 15 years (Ellis and Dosunmu, 2025; European Commission, 2009), whereas industrial chemicals under REACH receive permanent registration.

Detailed substance evaluation under REACH typically occurs only after a chemical has been placed on the market and in use, sometimes several years later (Dosunmu et al., 2025). This creates a key challenge for regulators in identifying risks to human health and the environment either prior to manufacturing or within short timeframe of use (Sweetman, , 2020). This issue is particularly evident as the examples of BPA, PFAS and FRs show that the 'substitution-first, assessment-later' approach enabled prolonged exposure to potentially hazardous chemicals (Dosunmu et al., 2025; Yang and Yu, 2025). Substance evaluation aims to clarify whether a chemical may pose a risk, providing authorities with a mechanism to request further data, "*. . .in case of suspicion of a risk to human health or the environment . . .* " (ECHA, 2021b). However, only a limited proportion of substances, around 20%, are prioritised for evaluation under REACH Article 44, using a risk-based approach focused on concerns such as PBT or wide-dispersive use (European Commission, 2023; UK HSE, 2025b). Slunge et al. (2023) report that no final conclusion on SVHC properties or regulatory action has been reached for about 90% of registered substances. As a result, regulatory action is often slow relative to the pace of chemical production, allowing potentially hazardous substances to remain on the market for extended periods (Dosunmu et al., 2025; Richter et al., 2021; Naidu et al., 2021). This necessitates the need to ensure only adequately tested chemicals are allowed market access (De Boer and Stapleton, 2019), hence the need for SVHC screening level evaluation during REACH registration.

When regulatory frameworks prioritise market access, they become reactive, creating the need to address problems as they occur as the PFAS example indicates (Dosunmu et al., 2025). This issue is amplified for a substance that is to be nominated under the Annex of the SC, evidence of adverse effects needs to be gathered which is only possible years after the substance is used, "*. . .it's worth noting that if we have epidemiological data, that means that people have already been exposed and potentially harmed. So that's a very reactive way of the system, the regulatory system for chemicals we want it proactive. So, we want to know before we expose humans and before we emit it into the environment and into our food and into our drinking water, we want to know the properties before that's happening . . .* Participant from Academia". From point of nomination to inclusion on the annexes of the SC, it could take years, elimination or restriction takes even longer.

Also, when SVHCs are restricted or prioritised for inclusion on the authorisation list, industry often shifts to other chemicals that are legally registered but not yet under regulatory scrutiny. As one participant from industry observed, "*. . .regulation does drive substitution and the substitutions are chosen from those chemicals which are already there and still registered on the market, which may or may not have a similar hazard profile . . .* ". The bisphenol example illustrates this, in 2012 global BPA consumption exceeded 6 million t/y, while EU production or import volumes for BPS were 1,000–10,000 t/y in 2014, and BPF was not yet registered. By 2023, BPS volumes had risen to 10,000-100,000 t/y and BPF reached 10-100 t/y (Yang and Yu, 2025). Such trends show how regulatory pressure on one substance can shift market demand to structurally similar alternatives. Over recent decades, several drop-in substitutes have been found to exhibit hazard profiles comparable to those they replaced as demonstrated for PFAS, BPA and FRs (Dosunmu et al., 2025; Maertens et al., 2021; Blum et al., 2019; Yang and Yu, 2025). Because these alternatives are technically new and may initially fall outside current regulatory focus, they enter the market rapidly even when their hazard profiles remain incomplete. When they later reveal similar risks, the outcome is an example of RS (Sweetman, 2020), "*. . .if you ban something . . . the sales of something else go up. But you don't know if that substitute is necessarily better . . .* Participant from Industry". BPA's restriction in thermal papers in 2020 led to a rapid switch to BPS, declared an SVHC 3 years later because of reproductive toxicity and endocrine disruption (ECHA, 2020c; ECHA, 2023a).

A related challenge arises from non-prioritised SVHCs for inclusion on the authorisation list. As of December 2025, 251 entries are listed as SVHC on ECHA's website, but only 59 had been added on the authorisation list as of that date (ECHA, 2025; ECHA, 2025b). The United Kingdom list as of December 2025 is smaller, with about 219 SVHC entries and 54 on the authorisation list since EU exit. Although SVHC identification signals concern and imposes certain obligations (e.g., ≥0.1% w/w in articles or at ≥1 t/y use), it does not restrict continued use. Contrarily, chemicals with significant sustainability concerns but not formally identified as SVHCs

may lack regulatory drivers for substitution, "*. . .if you've got something that's not a SVHC, but it might have a huge carbon footprint, there's no driver from REACH per se to substitute . . .* Participant from Industry". This reflects the reality that substitution is only one risk management strategy (Ujaczki et al., 2022; Lissner and Romano, 2011).

Replacing a known hazardous chemical with one whose risks remain poorly understood presents persistent regulatory challenge. Regulatory action typically requires a large evidence base, while alternatives often lack equivalent data. When regulators focus on urgent risk reduction, rapid substitution may be prioritised over thorough evaluation, leading to later discoveries that alternatives possess similar or even greater hazards (Dosunmu et al., 2025; Maertens et al., 2021). One participant from government noted regarding Cr(VI) alternatives, "*. . .we are certainly eliminating the carcinogenicity risk . . . but with boric acid, we will be bringing back other risks . . .* ". Industry responses to regulatory signals further shape substitution choices, often interpret regulatory action as implicit guidance on acceptable substitutes. This dynamic can shift environmental and health burdens rather than reduce them, as seen with PFOA and PFOS alternatives now attracting scrutiny (Dosunmu et al., 2025; Thiele et al., 2025; Hale et al., 2020), "*. . .and we constantly playing catch up . . .* Participant from Consultancy".

CLP plays a central role in identifying, classifying and communicating chemical hazards (European Commission, 2023). Its effectiveness, however, depends on the availability of adequate data. CLP itself contains no test requirements; data are generated under REACH and other legislative frameworks (European Commission, 2023). Without sufficient data, hazards may go unclassified, "*. . .if you don't have the data, you cannot use the criteria, and it can remain unclassified . . .* Participant from Academia". Since, regulatory risk management depends on accurate classification, delayed or absent classification can lead to regulatory actions being postponed, "*. . .unless a chemical gets classified, it's not considered hazardous . . . it's like the eye of the needle . . . the CLP is really important . . .* Participant from Academia".

The issue is exacerbated by exemptions for substances produced and used at <1 t/y under REACH (European Commission, 2006; van Dijk et al., 2021). This means such chemicals may enter commercial production without adequate information on their hazards and exposure. The EU chemical strategy for sustainability (CSS) notes that more knowledge is required for most chemicals including polymers and low volume substances (European Commission, 2020). Although the <1 t/y exemption supports innovation and allows the development of chemicals to bear their registration costs (European Commission, 2001); it can results in widespread use of chemicals that may never undergo regulatory review especially for advanced materials and nanomaterials, "*. . .you could end up with products on the market that have never been reviewed at all . . .* Participant from Association". The lack of an inventory of such substances further contributes to regulatory blind spots. Similarly, the SC requires nominations from Parties supported by extensive evidence, delaying scrutiny of chemicals not yet prioritised. Together, these factors increase the risk of unintended consequences such as RS.

4.2.2 Operational regulatory challenges

4.2.2.1 Balancing functioning of the internal market and risk management of chemicals, issues with authorisation

The aim of REACH authorisation is "*. . .to ensure the good functioning of the internal market while assuring that the risks from SVHCs are properly controlled and that these substances are progressively replaced by suitable alternative substances or technologies where these are economically and technically viable. . .*" REACH Article 55 (European Commission, 2006; ECHA, 2021a). Applicants must therefore analyse the availability, risks, technical and economic feasibility of alternatives (European Commission, 2006).

The authorisation process is designed to allow the functioning of the internal market, control the risks from Annex XIV chemicals and encourage their substitution. Substances on Annex XIV cannot be used beyond the sunset date unless an authorisation application is made or granted. Applications may follow the adequate control route or socioeconomic (SEA) route (European Commission, 2024; ECHA, 2021a; UK HSE, 2025a). Supporting information required with any application should include a chemical safety report unless previously submitted during registration, AoA, substitution plan where alternatives exist and a SEA analysis. Although SEA is optional under the adequate control route, applicants are encouraged to submit one, as "*. . .the Committee for Risk Assessment may reject an applicant's claim of adequate control . . . Applicants may therefore include a socio-economic assessment to show that the benefits outweigh the risks* (Art. 60 (4)). . ." (ECHA, 2021a).

The analysis of alternatives (AoA) is central to the authorisation outcome. It must demonstrate whether suitable alternatives exist, taking into account risk reduction potential, technical feasibility and economic viability. The quality of this analysis influences both the decision outcome and the review period (ECHA, 2021a). However, this structure can create incentives for applicants to argue that no alternatives are suitable as observed by a participant from government; "*. . .one of the disadvantages of the system is that as soon as a company decides that it wants to apply for authorisation, starts defending the current use . . . the company does everything to demonstrate that it cannot substitute. Whereas our interest would be to work with companies to identify where they can actually substitute . . .* ". Thus, although substitution is the intended outcome, the current approach may unintentionally reinforce argument against alternative suitability.

In practice, thorough assessment of alternatives is often limited due to data gaps or lack of adequate tools. For instance, comparing risks is particularly difficult for non-threshold hazards such as carcinogenicity or PBT/vPvB properties; "*. . .sometimes we end up comparing apples and pears . . . the chemical we're looking to start with has got particular concern, . . . a PBT or . . . an endocrine disruptor or it is a carcinogenic, mutagenic and reprotoxic (CMR). . . the alternatives . . . might not have those properties, but it might have different properties of concern and then you end up trying to compare . . .* Participant from Government". Limited data further complicates evaluation. The guidance on authorisation application states that applicants "*. . .are not obliged to generate new hazard data . . . nor must alternative risks be evaluated as thoroughly as those of the Annex XIV substance . . . if hazard*

comparisons or data gaps raise concerns, a more detailed risk assessment may be necessary . . . " (ECHA, 2021a), meaning applicants may rely on uncertainty to justify continued use and obtain favourable outcome or longer review period.

Suitability of alternatives is also dependent on the availability of alternatives in sufficient quantity or form (ECHA, 2021a; ECHA, 2021c). When suitable alternatives exist, authorisation may be refused or granted with a short review period. Under the SEA route, authorisation cannot be granted if suitable alternatives are available. However, if alternatives exist generally but are not feasible for the applicant, authorisation may still be granted if the socioeconomic benefits outweigh the risks and a credible substitution plan is provided (ECHA, 2021a). A participant from industry noted, "*. . .you have to show . . . why an alternative is not as good . . . because if there is a suitable alternative . . . you would not be given the authorisation . . . If the risk assessment . . . shows that it can be used safely and it's difficult to find an alternative, the authority may give a longer authorisation . . .* ".

Authorisation decisions are therefore influenced not only by chemical risk or scientific evidence but also by socioeconomic factors, technical performance needs, political context and feasibility of alternatives. These considerations can reduce incentives for substitution and create opportunities to justify continued use. Once authorisation is granted, organisations may have little motivation to substitute unless the sunset date is missed (Ujaczki et al., 2022). Political priorities further influence outcomes. In the EU, although scientific committees evaluate applications, the Commission makes final decisions, requiring agreement across Member States. Similarly, under the SC, the Conference of the Parties (COP) decides on all listing proposals, while in the United Kingdom, authorisation decisions are made by the Secretary of State for Environment, Food and Rural Affairs (UK Government, 2025; Stockholm Convention, 2025). Political decision making often reflects national interests and public opinion, "*. . .this restriction process . . . is a scientific process . . . but then . . . you come to the political process . . . sometimes the country with a strong chemical industry and the country producing the substance . . . might not fully support that restriction . . .* Participant from Government". Decision is based on the need to balance the risks from the use and exposure of the chemical and ensure continuity of the internal market. Scientific evaluation and political decisions need to converge, otherwise divergent views may delay decision making, impact the final outcome and reduce incentives for safe(r) substitution.

4.2.2.2 Can't speak, won't speak, barrier to transparency and information sharing

Effective communication across the supply chain is fundamental for substituting hazardous chemicals with safe(r) alternatives. Informed substitution depends on transparent, robust hazard data, exposure and functional performance (Maertens et al., 2021; Bechu et al., 2024). However, communication is often hampered by confidentiality and competition-law constraints, which limit the extent to which information can be shared. Confidential business information (CBI), intellectual property protections, and competition rules restrict disclosure (ECHA, 2023c; ECHA, 2025c), a participant from government states, "*. . .people will tell us about alternatives in very broad terms, kind of chemical classes or big family groups, but it's very hard to get specific information out of people . . . we can only ask nicely, and hope people tell us . . .* ". While these protections support market competitiveness and innovation, they can inadvertently impede information sharing needed for sound substitution decisions, increasing the likelihood of RS (Maertens et al., 2021; Rudisill et al., 2023).

Although REACH requires communication of hazard and risk information across the supply chain, safe use demonstrations made upstream often do not reflect conditions downstream. Exposure scenarios in extended safety data sheets may assume operational conditions and risk management measures that may differ from actual downstream practice (ECHA, 2016). Fransman et al. (2023) found that downstream users frequently face complexity, unclear instructions, and limited opportunities for feedback, leading to misalignment between upstream documentation and actual downstream use, "*. . .although downstream users are covered by REACH in terms of . . . risk assessment, in practice, most producers write their risk assessments without consulting . . . downstream users and in fact downstream users don't usually want to tell their suppliers what they're doing anyway . . .* Participant from Consultancy". When information is unclear or not shared, it undermines safe use communication and reduces the incentives for safe(r) substitution.

Regulatory design further constrains information flow. Under REACH, registrants must provide information when formally requested, for example REACH Article 46 (2) states "*the registrant shall submit the information required to the Agency by the deadline set*". In contrast, third party information such as from alternative suppliers, downstream users and civil society entirely depends on voluntary public consultations. These submissions can be critical, as applicants may be unaware of available alternatives and authorities often learn of them only through third party input. Technical, economic, and safety information provided by third parties can shape the assessment of an alternative's suitability. Their impact depends on the clarity, quality, and detail of the information, particularly regarding feasibility and risk reduction (ECHA, 2021a). Such consultations are essential during authorisation and restriction processes because data on alternatives can lie outside registration dossiers and applicant submissions. However, voluntary engagement limits both the nature and completeness of information available, affecting decisions on review periods, derogations, and assessment of technical and economic feasibility (ECHA, 2021a; Rudisill et al., 2023). For example, a participant from Government notes that little or no information was declared by third parties during the authorisation consultation for lead chromate. Confidentiality obligations and competition rules can therefore lead stakeholders to withhold relevant information, while downstream users may avoid disclosing the evidence base needed to support informed decisions and effective substitution outcomes.

Comparable challenges also appear under the SC, while the POPRC must gather detailed information of uses, emissions, and alternatives, the system similarly relies on voluntary submissions. "*. . .Information useful for the identification of alternatives may be collected through consultations . . . care should be taken to handle confidential business information appropriately . . .* " (UNEP, 2009). When information gaps persist as a result of confidentiality and competition rules, this can create conditions where those willing to

share information cannot, and those unwilling to share are not compelled, thereby restricting transparency and slowing progress toward safe(r) substitution. A participant from government noted, incentives to provide information are strong during REACH registration, but much weaker when identifying alternatives for restriction or authorisation, "*. . .when it comes to possible alternatives . . . incentive . . . is weaker or more much more complex . . .* ". These information gaps can limit regulators and policymakers' ability to fully assess the feasibility, performance, and risk of potential alternatives, increasing the likelihood of RS (ECHA, 2023c). Consequently, confidentiality barriers, voluntary consultation mechanisms, and uneven stakeholder engagement can create systemic information asymmetries that constrain collaborative decision making, and hinder timely, effective and safe(r) substitution of hazardous chemicals.

4.2.2.3 Fight or flight, pressure of time-driven regulatory decisions

The identification of a chemical as SVHC under REACH or its nomination for inclusion on the SC's Annex triggers regulatory pressure for control and phase out. For example, F. Hoffmann-La Roche Ltd. was committed to phasing out all SVHCs from its products and processes within 10 years of a substance being added to the Candidate List, driven by the rapidly growing number of listings and the desire to set measurable sustainability goals (Ujaczki et al., 2022). Under REACH, authorisation is granted with a time limited review period within which substitution is expected and granted authorisations can be amended or withdrawn if new information emerges (European Commission, 2006; ECHA, 2021a). Such uncertainty imposes time pressure on industry to find alternatives quickly. When a chemical is proposed for restriction or ban, organisations must find alternatives within the available time for business continuity, "*. . .there's always derogations . . . timeframes for chemicals to be phased out. We understand completely that this is not an overnight job . . .* Participant from NGO".

Short windows for finding alternatives can trigger urgent substitution decisions where speed is prioritised over robustness. Imminent regulatory deadlines such as sunset dates, bans or listing decisions, often push companies toward structurally similar drop-in replacements that can be implemented quickly and at scale. Following 3M's voluntary phaseout of PFOS in 2002, substitutes such as PFHxS and PFBS were rapidly introduced (Dosunmu et al., 2025; Hale et al., 2020), PFBS was later added to EU Candidate List in 2020 due to probable serious human health and environmental effects (ECHA, 2025d). These substitutes are often used based on limited hazard or exposure data, especially when regulatory frameworks do not require equivalent evidence for alternatives, "*. . .you need time to generate the new data, check that it's valid and then implement it into your supply chain . . . that, I think is the main challenge . . .* Participant from Industry". Under such pressure, substitution decisions tend to rely on structural similarity, equivalent performance, and short-term compliance, rather than comprehensive assessment of long-term fate, toxicology and exposure. Resulting in replacing hazardous substances with alternatives later shown to have comparable risks as with PFAS, BPA and FRs. Regulatory action and pressure may successfully remove the targeted substance but unintentionally perpetuates the underlying risks through closely related chemicals.

Time limited deadlines, business needs and changing regulatory requirements create a high-pressure environment in which staying ahead of regulation becomes essential sometimes triggering a 'fight or flight' response. However, setting deadlines requires balancing incentives for substitution with the need to protect health and the environment, "*. . .if we are setting a deadline . . . which is very late, for example, in 15 years . . . , in the immediate days, no incentive to substitute because companies will know that they have 10 more years or 15 more years, so they will not invest right now . . . also setting a deadline which is far away . . . is not the solution . . .* Participant from Government". Where deadlines are short, for business continuity purposes, an organisation will follow the path of least restriction, which is drop-in replacement using chemicals with similar functions or properties. Substitution often takes several years with the clock resetting each time an alternative fails or risk identified (Dosunmu et al., 2025; Ujaczki et al., 2022).

4.2.2.4 Limited regulatory capacity, monitoring and enforcement

The regulatory capacity of authorities to design, implement, and enforce chemical regulations plays a central role in determining how hazardous chemicals are managed and substituted. Well-resourced agencies with strong scientific and technical expertise can provide clearer guidance on safe(r) alternatives, enforce compliance, and incentivise innovation (ECHA, 2020b). This increases the likelihood that substitution is strategic, targeted, and genuinely safe(r), reducing the risk of RS. However, authorisation and restriction under REACH are resource-intensive processes, similar to that faced by the POPRC under the SC (Figuière et al., 2023). Industry especially SMEs is similarly constrained. Limited regulatory capacity can create gaps that hinder effective substitution, as agencies with insufficient resources may struggle to assess hazards comprehensively, evaluate alternatives, or track chemical use across sectors. Globally, regulatory assessments lag behind the scale and diversity of chemicals in commerce (Brack et al., 2022).

Timely risk management depends on regulatory expertise and resource availability. For chemicals, this expertise is sometimes available within organisations, leaving regulators without key insights into function/performance, or use, further slowing risk management. Slow regulatory decisions can delay substitution efforts, prolonging exposure to hazardous chemicals. A participant from government explained, "*. . .*restrictions *. . .* depend on what the Member States are prepared to do and what resources they have . . . this could . . . result in skewed approaches . . . ". Insufficient capacity can also slow the identification and prioritisation of SVHCs for REACH Annex XIV, restrictions, or bans, "*. . .*we still lack some speed . . . there are still a lot of chemicals that fulfil criteria . . . we need more speed . . . Participant from NGO".

In authorisation, regulators must judge applicant's information on alternatives or assess claims that no suitable substitutes exist. Knowledge gap and capacity constraints can make it difficult to challenge substitution plans or effectively enforce regulations, "*. . .it might be very hard for regulators to judge . . . what degree of . . . less performance is acceptable . . . or whether whole production processes*

must change . . . Participant from Government". The SC is also not immune from the challenges with regulatory speed. PFOS was listed in 2009, followed by PFOA 10 years later in 2019, PFHxS in 2022, and long-chain perfluorocarboxylic acids (LC-PFCAs) in 2025 (UNEP, 2025b). Each listing took years from nomination to adoption, demonstrating slow global regulatory action (Dosunmu et al., 2025). In the EU, although an estimated 1,500 substances had SVHC properties in 2013 (European Commission, 2013), only about 455 had been added to the candidate list by 2022, indicating slow progress (Figuière et al., 2023).

A further challenge is limited knowledge of regulatory agencies on industrial processes. Agencies depend heavily on industry submissions such as substitution plans, yet these may be incomplete, aggregated, or framed in ways that obscure process-specific exposures or substitution challenges. ". . .*The alternatives are often relatively uncertain to us . . . we don't have the . . . industry-specific knowledge* . . . Participant from Government". Without detailed understanding of functional requirements, supply-chain dependencies, or certification constraints, regulators may misjudge exposure pathways or design measures that are difficult to implement. Industry also experiences knowledge gaps, since experience with alternatives sometime depends on supply chain position, ". . .*the farther you are away from the real substance user, if you are downstream industry for example an automotive or electro industry, they get their parts and there is some essential chemical that are somehow found in polymer, and they don't have any idea how to substitute it, but they're still the user* . . . Participant from Consultancy". These knowledge gaps can slow regulatory action, lead to poorly targeted restrictions, or encourage industry to adopt minimally disruptive substitutes that maintain process compatibility but perpetuate underlying risks.

Weak regulatory enforcement and monitoring can significantly increase the risk of RS by weakening the link between regulatory decisions and real-world outcomes. When authorities lack the capacity to systematically track emissions, uses, and downstream impacts of alternatives, risks may only be detected after widespread adoption has occurred. The European Commission notes, ". . .*creating a toxic-free environment requires more action to prevent pollution . . . better monitor, report, prevent and remedy pollution* . . . " (European Commission, 2019). Despite this, enforcement remains uneven and fragmented. Under the EU CSS, enforcement of chemicals legislation is described as "unequally effective" due to varying national capacities (European Commission, 2020). One NGO participant highlighted, ". . .*some Member States do a lot of work to enforce, some do very little . . . there is a need to improve the level playing field . . .* ". Uneven enforcement weakens the incentives for substitution by removing accountability mechanisms that drive change.

Weak or unpredictable enforcement can discourage firms from investing in safe(r) alternatives, placing innovators at a competitive disadvantage relative to those that continue using hazardous chemicals without consequence (OECD, 2021). Organisations may forgo investment in research and development if they believe oversight is unlikely or inconsistent, prolonging reliance on hazardous substances and slowing innovation (Rudisill et al., 2023). Under REACH, authorisations are time-limited, and holders are expected to work toward substitution; however, no formal monitoring occurs during the authorisation period. Authorities only discover whether substitution has occurred at reapplication (ECHA, 2021a). As one government participant observed, ". . .*companies are not required to . . . frequently update us . . . only on . . . requesting a reauthorisation* . . . ". Inadequate monitoring can enable poorly assessed alternatives to enter the market, increasing the likelihood of RS and perpetuating environmental and health harms (Bechu et al., 2024). Without strong oversight, substitution becomes voluntary rather than mandatory, undermining regulatory effectiveness and slowing the transition to safe(r) chemicals (ECHA, 2020d). Enforcement challenges also extend to the SC, where limited monitoring capacity, inconsistent national implementation, and resource constraints hinder compliance and slow POP phase-outs (Akinrinade et al., 2024; UNEP, 2025c). These gaps reduce incentives for global substitution and prolong exposure to persistent hazardous chemicals. Across both EU and international frameworks, disparities in enforcement and monitoring capacity can weaken regulatory outcomes and create uneven pressures on industry. This undermines the effectiveness of chemical management systems and increases the likelihood of RS, even when strong regulatory intentions exist.

4.2.2.5 To group or not to group – the challenge of substance grouping

Traditionally, substance evaluation and risk assessment have followed a substance-by-substance approach, which is laborious, slow, and can delay risk management. This approach unintentionally encourages RS, as substitution decisions are shaped by regulatory outcomes (Figure 2D). Regulatory drivers are especially important where alternatives are more expensive, require reformulation, reduce performance, or introduce unfamiliarity for users (European Commission, 2024). When a substance faces regulatory action, organisations typically turn to structurally and functionally similar replacements that are already registered and not currently under regulatory scrutiny. A participant from industry noted, ". . .*when you remove a chemical from the environment . . . the market will look for alternatives . . . many of those alternatives will already be out there and they'll already be registered . . . often . . . with a very similar profile . . . example BPA/BPS* . . . ". A similar pattern emerged with PFAS; when PFOA and PFOS were restricted, industry rapidly introduced related alternatives that initially faced little regulatory control. This creates a constant cycle of 'regulate and replace' between regulators and industry (Dosunmu et al., 2025). ". . .*In the past we dealt with substance by substance . . . that very often lead to one substance being replaced by another one which is less well researched . . . it doesn't really resolve the problem . . . it's just another substance that comes in of the same family* . . . Participant from Government". This issue can be exacerbated when the focus is to address a specific risk e.g., persistence which results in the use of alternatives that address one risk but create another especially when the alternative is only tested for the hazard of concern (Maertens et al., 2021).

To address this, regulatory agencies are increasingly moving toward group-based approaches. ". . .*This is why we have started working more with broad restrictions . . . the proposal for a universal ban of PFAS . . . dealing with all of them at the same time . . . that brings a lot of complexity. Things that that haven't been thought of at the time of proposing the restriction and that bring us back to this first*

area where we have a lot of trade-offs and it's very unclear how to proceed. That creates a lot of discussions, delays in the proposals, so also delay for environmental protection but also uncertainty for industry . . . Participant from Government". Grouping can increase the complexity, time and resource intensity of risk management processes and may delay regulatory intervention, especially where data are fragmented or uneven across group members. Nonetheless, grouping is used to protect human health and the environment (Wohlleben et al., 2023), as seen with PBDEs, PFOA salts, and PFOS salts. REACH (Annex XI, Section 1.5) permits grouping when substances display similar patterns in physicochemical, toxicological or ecotoxicological properties. However, broader application of grouping has been limited until recently. The universal PFAS restriction proposal marks an important shift and sets a new precedent for class-level management (Dosunmu et al., 2025; ECHA, 2025e). Yet grouping is not a universal solution, "*. . .grouping is not a solution to all regrettable substitutions . . . you can get burden shifting . . . an example Montreal Protocol . . . CFCs replaced with HCFCs then HFCs with high global warming potential* . . . Participant from Academia".

Within the EU, ECHA's Integrated Regulatory Strategy aims to accelerate data generation, identify substance groups of concern, and expedite regulatory action. The Assessment of Regulatory Needs (ARNs) groups structurally similar chemicals to prioritise them (ECHA, 2022). While grouping is commendable, its effectiveness is limited by data availability and the extent of the evidence required to support or justify the approach making any substance grouping narrow and sometimes insufficient, as illustrated by the restriction of BPA in the EU and PFOA/PFOS under the SC. BPA was proposed for restriction in thermal paper in 2016 because sufficient evidence of endocrine disruption existed; however, BPS suspected of similar properties at the time was excluded due to insufficient data and need for further evaluation (CHEMTrust, 2015). As one participant from government stated, "*. . .that body of literature was very much available for BPA . . . for the other bisphenols . . . research is much less available . . . so . . . difficult to get a group restriction . . .* Participant from Government". Yet BPF and BPS subsequently became BPA substitutes, forcing regulators to later pursue a group restriction banning BPA and other bisphenols in food contact materials (European Union, 2024a).

The extent of the evidence required to justify grouping continues to pose challenges in regulatory decision making. While chemical grouping can address regulatory capacity limitations and prevent RS, it also raises challenges related to scientific uncertainty, data gaps, and the risk of over- or under-regulation. To propose a group of chemicals for regulatory risk management, authorities are required to generate and assemble a transparent justification of the similarity of the group, including boundaries which may be exacerbated by lack of data. This challenge was highlighted by a participant from government "*. . .after BPA restriction, the discussions came on the other bisphenols . . . we are years ahead now and we're discussing the grouping of bisphenols. it takes a while . . . that is because it's also complex, you have to be sure how to group, what is your scientific basis to group the bisphenols based on the same toxicological mechanism . . . otherwise you lose in court of course. You have to be quite sure that all the chemicals are in the same group have the same mechanism of action and the same . . . adverse effects on humans, for instance, and/or on the environment . . .* ". Also, UV-328 was added to the SC Annex A in 2023 for elimination, the nomination and decision whether to include other UV-328-related chemicals was considered but dropped due to lack of sufficient evidence to support this; "*. . .when Switzerland nominated UV-328, it was a big discussion if we should nominate just UV-328, or should we nominate group of substances for example like all UV, benzotriazoles at once? . . . at the end, we decided against this group approach, . . . the reason was that at least for UV-328 we have the best data . . .* Participant from Academia". For a chemical to be nominated for inclusion on the SC, extensive evidence is required to be gathered, presented and justified by the nominating party. While this is an important and necessary step, the use of precautionary approach is required to prevent continuous cycle of RS and avoid 'paralysis by analysis' (Harremoes et al., 2013).

5 Conclusion

This study sets out to examine whether chemical regulations specifically the EU/United Kingdom REACH and the SC may unintentionally exacerbate RS. Drawing on online survey responses, in-depth interviews with professional stakeholders, and regulatory document analysis, the findings indicate that both REACH and the SC can, under certain conditions, inadvertently perpetuate RS through a combination of systemic and operational challenges. Whilst survey results reveal mixed views, overall, a substantial majority of government respondents (around 70%) agreed that chemical regulations can exacerbate RS. At the same time, participants overwhelmingly agreed that data availability and interpretation strongly influence substitution decisions and that regulation remains a major driver of substitution.

The thematic analysis identified interconnected regulatory mechanisms through which RS may arise including fragmented and uncertain regulatory landscapes, trade-offs between internal market functioning and risk management, limitations in data availability and interpretation, communication barriers, and divergent regional regulatory approaches (Figure 3). Consistent with the study's focus on regulatory influences, other drivers of RS such as customer demand (Figure 2D) were not examined, and the findings should therefore be interpreted within this defined analytical scope. Nevertheless, the results provide fresh evidence that while regulation is essential for promoting the substitution of hazardous substances, features of regulatory design and implementation can unknowingly hinder the selection of safe(r) alternatives. Where market access is prioritised over robust prior evaluation, or where regulatory capacity and coherence are limited, the risk of substituting one hazardous substance with another increases, as illustrated by the cases of PFAS, bisphenols, and FRs.

More broadly, the findings highlight a recurring regulatory cycle in which chemicals are rapidly adopted to meet societal demand, concerns emerge only after widespread use, and substitution pressures then create conditions for further unintended harm. When replacement chemicals are insufficiently assessed, regulatory blind spots can emerge, increasing the likelihood of successive cycles of RS and compounding environmental pressures, including chemical and biodiversity loss. Addressing these systemic and operational weaknesses is therefore urgent to

understand how regulatory frameworks can be better designed or adapted to prevent RS. Future research should build on these findings by examining how similar regulatory dynamics operate in other jurisdictions, such as the United States and Australia, to support more effective and globally coherent approaches to preventing RS.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Lancaster University Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

OD: Investigation, Writing – original draft, Formal Analysis, Conceptualization, Methodology, Writing – review and editing, Data curation. RW: Investigation, Conceptualization, Writing – review and editing. AM: Writing – review and editing, Investigation. NW: Investigation, Writing – review and editing. AS: Funding acquisition, Supervision, Writing – review and editing, Investigation.

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Conflict of interest

Author RW was employed by WSP, Reading.

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