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Regulating “forever chemicals”: social data are necessary for the successful implementation of the essential use concept

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Abstract

Per- and polyfluoroalkyl substances (PFAS) are a large class of synthetic compounds, many of which are persistent, mobile and toxic (PMT). The sheer number of PFAS makes a substance-by-substance based approach to regulating this group unfeasible. Given the known risks of many PFAS, a precautionary approach (i.e., the Essential Use Concept; EUC) has been called for, whereby any substance is assumed to be harmful and should be phased out, unless it is shown that: (a) the use of this substance is necessary for health and safety, or is critical for the functioning of society and (b) there are no available technically and economically feasible alternatives. While experts, including chemists and toxicologists, are well-placed to assess the second criteria, determining what is necessary for the “functioning of society” requires a wider consideration of societal beliefs and preferences and greater involvement of various interested and affected parties, especially those whose voices are less heard but may be most vulnerable. The aim of the current paper is to provide a preliminary framework and research agenda outlining why and at what points in the essential use decision-making process broader societal perspectives are required, and how such ‘social data’ can be collected. The ultimate goal is to improve chemicals management by supporting citizens in becoming more informed and engaged participants in relevant debates and policies, including in how to operationalise the EUC.

Keywords PFAS, Essential use concept, Social data, Risk perception, Chemical regulation, Chemical policy

Introduction

Human-made chemicals bring many benefits to human society; however, some also present short- and/or long-term risks to both human and environmental health [1]. Various approaches to managing the trade-offs between a chemical’s benefits and the risks from its hazardous properties and environmental exposure exist, including classic risk-based assessment versus precautionary-based approaches, as well as more recent proposals for “safe-and-sustainable by design” [2–5]. Where the risks are substantial and the traditional risk management options have had limited success, production restrictions and use bans have been implemented, e.g., for chlorofluorocarbons (CFCs) [6]. The evidence suggesting that the class of chemicals called per- and polyfluoroalkyl substances (PFAS) falls into this latter category is growing. PFAS substances are consistently found to be “persistent”, “mobile” in the environment and “toxic”, seriously challenging the feasibility and effectiveness of mitigation-related risk management approaches [7].[1] Furthermore, with over 10,000 different PFAS, a case-by-case approach

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[1] We also acknowledge that some are calling for ‘hazard assessment’ over risk-based assessments (e.g., in the EU Chemicals Strategy for Sustainability). However, given that the psychological and behavioural work we introduce in this paper focuses on ‘risk perception’, not ‘hazard perception’, we refer to risk throughout the paper.

to risk assessment and management is unfeasible, leading some researchers to call for a precautionary, class-wide ban on the basis that most, if not all, PFAS will prove to be harmful in the long run [8, 9].

However, even those who support the restriction of PFAS also recognise that, as with CFCs, there may be some special cases where the societal benefits of specific PFAS uses still outweigh the risks. These instances have been referred to as "essential use" cases [10], but a lack of clarity over what "essentiality" means in modern societies is hampering consensus on legislative action [11]. To date, input into the PFAS-related "essential use" debate appears to be driven by those with either an economic interest in maintaining PFAS use, i.e., the chemicals industry [12–14], or scientists and toxicologists presenting data of the chemicals' harmful effects [15–18]. However, the issue of essentiality goes way beyond these two groups and includes the whole of society. While some citizens may experience a net-benefit from a given chemical product, others may experience a net-harm, and bringing these perspectives and lay knowledge into the debate has long been recognised as good chemical risk management practice [19, 20]. This need for the better integration of society in decision-making has been echoed more recently in the case of PFAS [21], and in chemical water pollution more generally [1].

Despite these recommendations, the broader societal perspective does not yet seem to have been incorporated into the debate on whether and how to adopt an "essential use" approach to the management of PFAS. The aim of the current paper, therefore, is to provide a framework and research agenda outlining why, when and how to collect the kinds of 'social data' needed to ensure citizen's perspectives are heard, and moreover to achieve a 'social consensus' on what makes a given use 'essential' or not. Although the term 'social data' can be interpreted in different ways, here we define it as data describing and predicting perceptions, understandings, evaluations, intentions and actions of individuals, communities and societies more broadly, as well as their interactions with each other and with their environment [22]. We define 'social consensus' as the degree to which people in society are in agreement about an issue [23]. While acknowledging that all voices have value in and of themselves in democratic societies, we also recognise the complexity of these issues and the desire of many decision-makers to ensure citizen perspectives are as informed as possible. Thus, our research agenda does not merely outline how to collect current perspectives, including possible misunderstandings and misinformation, but discusses also how to develop a better understanding of these issues in society. The ultimate aim is to create a process of supporting an informed and engaged public to become active participants in a decision-making process that should ultimately minimise PFAS impacts on human and environmental health.

The paper proceeds as follows. First, in Sect. "Background, key concepts and challenges", we begin by briefly outlining the issues surrounding PFAS, current regulatory processes, what the 'essential use concept' means in the current context, as well as some of the challenges to successfully implementing the EUC.[2] Sect. "Using social and behavioural science to bridge the gap in the EUC" forms the core, namely, our "research agenda" and discusses where, when and how diverse societal perspectives may be most useful in the decision-making process and presents various social and behavioural science approaches to collecting the kinds of social data we need to support this process. This includes qualitative and quantitative methods, inspired by a "mental models" approach to risk. Given the importance of supporting citizens in becoming more "informed" of the issues, Sect. "Using social and behavioural science to bridge the gap in the EUC" discusses the role of PFAS-related science communications and citizen panels in supporting these efforts. Sect. "Using social and behavioural science to bridge the gap in the EUC" also provides an example of how social data collection can be used with experts to help understand perceptions of the EUC (see Box 1). Finally, Sect. "Conclusion" provides some brief conclusions.

Background, key concepts and challenges

The problem with PFAS

PFAS are a large class of synthetic compounds, including perfluorooctanoic acid (PFOA) and perflourooctane sulfonic acid (PFOS), which were the first PFAS to gain attention due to their ubiquitous occurrence and documented negative effects on human health and the environment [24]. Over 10,000 individual PFAS, often referred to as "Forever Chemicals", have been identified [24, 25]. Uses include in construction, biotechnology and the energy sector and everyday products including non-stick cookware, clothes, cosmetics and personal hygiene products [26]. While PFAS are diverse in terms of structure, properties, uses, bioaccumulation potentials and toxicities, all PFAS contain perfluoroalkyl moieties that are extremely resistant to environmental and metabolic degradation [7]. They will continue to persist in and affect the natural environment, over time increasing the levels of PFAS that humans are exposed to. This is concerning

[2] We focus mainly on the EU context (i.e., in relation to the implementation of the EUC within REACH and the CSS), but acknowledge that there are cases within the US in which the EUC is currently being implemented (e.g., in Minnesota).

given the health risks associated with greater levels of PFAS exposure. Of the relatively few well-studied PFAS, most are considered moderately to highly toxic, with an increased risk of several forms of cancer, thyroid disease, higher cholesterol levels, infertility and developmental effects in foetuses and children [15–18, 27, 28], making many of them "*substances of very high concern*" under EU chemical regulation.[3]

PFAS pollution is now ubiquitous in the environment across Europe [29] with specific examples detected in air, soil, plants and biota globally [30, 31]. Contamination of drinking water supplies in several European countries has been observed [32, 33]. In some highly polluted areas, e.g., Veneto, Italy [34], drinking water concentrations of perfluorooctanoic acid (PFOA) and perfluorosulfonic acid (PFOS) are above the limit for individual PFAS levels proposed in the EU Drinking Water Directive [35]. There are other EU countries that now face widespread PFAS pollution and significantly polluted areas include Belgium [36] and the Netherlands [37]. Costs to society arising from PFAS exposure are predicted to be high: e.g., the indirect costs of a lack of PFAS remediation (i.e., to human and environmental health) in contaminated land around a single Swedish airport was estimated to be approximately 7.5 million Swedish Kroner (~ US$ 670,000) annually [38]. Similar costly remediation cases have occurred in Germany and Denmark [39].

Current regulatory approaches and the introduction of the EUC

The standard approach to chemical regulation is "risk-based" where decisions are based on the best available scientific evidence with respect to the likelihood and potential severity of any harms: one must demonstrate that a specific substance is harmful to the extent that it should be restricted [2, 3]. Interventions on a particular substance use should be targeted, proportional, effective and efficient, to avoid safe and useful substances being overly restricted [40]. However, the EU Chemicals Strategy for Sustainability Towards a Toxic Free Environment (CSS),[4] highlights that the sheer number of PFAS in existence renders a substance-by-substance risk assessment approach economically and practically unfeasible [41]. Kwiatkowski et al. [8] proposed a class-wide-ban, given the high mobility, persistence, bioaccumulation potential, and toxicity (both known and potential) of PFAS studied to date. This approach treats all PFAS as a single class, assuming them to be problematic until sufficient evidence to the contrary, in line with the precautionary principle approach [4]. This is consistent with one of the key conclusions from the European Environmental Agency's (EEA) "Late Lessons from Early Warnings" [19] report which argued that regulators should "*avoid 'paralysis by analysis' by acting to reduce potential harm when there are reasonable grounds for concern*" (p.169).

One proposal to avoid "*paralysis by analysis*" in the PFAS domain is the adoption of the EUC [10]. The EUC builds directly on the notable success of the Montreal Protocol (1987) which established global consensus in support of the reduction of ozone-depleting substances (i.e., CFCs). It remains the only environmental treaty ratified by all 198 UN Member States, and it regulates the production and consumption of around 100 anthropogenic chemicals [6]. Importantly, the Montreal Protocol does not propose a class-wide CFC ban under all conditions. Rather, it suggests there may be some specific contexts where their benefits are so significant that the known risks can be tolerated. Specifically, it suggests that CFCs may be essential when (p.131):

1. *It is necessary for the health, safety or is critical for the functioning of society (encompassing cultural and intellectual aspects); and*
2. *There are no available technically and economically feasible alternatives or substitutes that are acceptable from the standpoint of environment and health.*[5]

Building on these core principles, Cousins et al. [10] emphasised that *"this essentiality should not be considered permanent; rather, a constant pressure is needed to search for alternatives..."*, thus driving down and ultimately phasing out PFAS uses over time. This resulted in the development of three proposed categories of essential use to guide decision-making on PFAS regulation (p.1805):

1. *"Non-essential"—Uses that are not essential for health and safety, and the functioning of society. The use of substances is driven primarily by market opportunity.*
2. *"Substitutable"—Uses that have come to be regarded as essential because they perform important functions, but where alternatives to the substances have*

[3] See: https://www.oecd.org/chemicalsafety/portal-perfluorinated-chemicals/countryinformation/european-union.html.

[4] See: https://echa.europa.eu/hot-topics/chemicals-strategy-for-sustainability.

[5] In addition, under the Montreal Protocol, for any essential use it must be demonstrated that '*all economically feasible steps have been taken to minimise the essential use and any associated emission of the controlled substance, and the controlled substance is not available in sufficient quantity and quality from existing stocks of banked or recycled controlled substances, also bearing in mind developing countries' need for controlled substances.*'

Table 1 Example cases of "critical" and "necessary" uses of chemicals when assessing essentiality

Step 1. Assessment of criticality and necessity	
Is the use* of the substance necessary for health and/or safety?	Is the use* of the substance critical for the functioning of society?
Necessity should be assessed by demonstrating and verifying whether a use is necessary for any of the following elements • Preventing, monitoring or treating severe health issues • Sustaining basic conditions of human life and health • Managing and preventing health crises/emergencies • Personal safety • Public safety • Addressing a danger to animal health which cannot be contained by other means	Criticality should be assessed by demonstrating and verifying whether a use is critical for any of the following elements • Providing resources or services which are critical to society • Managing societal risks and impacts from natural and man-made crises and emergencies • Protecting cultural heritage • Running traditional and religious practices • Protecting and restoring the natural environment

From European Commission report on developing the EUC, Bougas et al. [49]

*The authors note that: "Use should be assessed through considering societal need for the technical function provided by the most harmful chemical in a specific end use (e.g., final product) in a defined setting" (pg. 7)

now been developed that have equivalent functionality and adequate performance [...].

3. *"Essential"—uses considered essential because they are necessary for health or safety or other highly important purposes and for which alternatives are not yet established.*

In keeping with, but also extending the Montreal Protocol, the EUC argues that PFAS should only be used when they are deemed necessary for health, safety or other "*highly important*" purposes and where no obvious substitute "*yet*" exists. Additional work posits that technical substitution under the EUC might work via different kinds of substitution routes. Through "functional substitution", Tickner et al. [42] suggest reorienting chemical management approaches away from time-intensive risk assessment based on single chemicals towards comparative evaluation of the best options to fulfil a specific function. That is, can we achieve the same or comparable result with drop-in (chemical) alternatives, or by changes to the materials, process or end product in which the chemical is used? Indeed, such an approach is useful in expanding upon options for alternatives under point 2 of the EUC [43, 44]. However, we note that this work thus far does not help to more clearly define exactly what makes something "essential" under point 1 of the EUC.

Current obstacles to the EUC

In the European Union, the EUC was deemed not yet fit for inclusion in the 2023 broad PFAS restriction proposal, submitted by five European member states under the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) framework [45]. Here, we outline some of the obstacles the EUC is facing to implementation, culminating with a discussion on how social data might improve the EUC's defining criteria and support a more successful implementation. Though we focus on the issue of defining the criteria of essentiality, we recognise that there are likely to be a range of external pressures acting on (or rather against) the implementation of the EUC, as well as the phasing out of PFAS in general (e.g., including the downplaying and/or suppression of data on the immunotoxic properties of PFAS [46], as well as lobbying that has helped to create decision paralysis by raising scientific uncertainty and doubt around the risks of PFAS [47]).[6]

Lack of well-defined criteria One of the reasons given for omitting the EUC from the PFAS restriction proposal was a lack of clear legal criteria on how to decide exactly what is "essential for society" (see Q&A 2.18) [48]. The European Commission has since released a report detailing stakeholder views on key matters related to the EUC [49]. Stakeholders comprised, for example, industry, public authorities, academic researchers, and NGOs. Feedback was gathered via a workshop, targeted survey and interviews. This report expanded upon the criteria for essential use, proposing the examples below as cases which constitute necessary or critical functions (see Table 1).[7] While indeed useful to have stakeholder-informed ideas on what could make a use essential, we note a lack of views from non-professional stakeholders, that is, the non-expert public and different groups of the public whose demand for goods and services ultimately plays an important role in determining PFAS manufacture and use.

Fairness considerations Further, the report takes little account of equity issues in terms of either particularly vulnerable individuals (e.g., children, older adults)

[6] See also the Corporate Observatory Europe's press release on evidence of lobbying against the EUC: https://corporateeurope.org/en/2024/01/how-chemical-industry-lobby-pushes-safe-use-exemptions.

[7] N.B. as of April 2024, the European Commission released updated essential use criteria document. However, as the updated criteria is very similar to that in the Bougas et al. [43] report, we find that it similarly lacks widescale social data to support it.

or socio-economically disadvantaged groups who historically tend to live in more polluted areas in general. A lack of attention to such environmental injustices is sadly not unique to PFAS, and a considerable body of work has examined how to engage affected individuals and publics in decision-making processes [50, 51]. For instance, it is widely shown that poorer neighbourhoods suffer with worse air quality than do richer ones [52, 53]. And higher levels of pollution are often linked to poorer neighbourhoods' proximity to industry sites [54]. These kinds of considerations are also particularly relevant to PFAS, given that communities close to sites producing and/or using PFAS have suffered adverse exposure effects (and moreover, "non-experts" within some of these communities have been forced to provide evidence of these detrimental effects themselves, with some industry and authorities downplaying the risk; e.g., see [12, 55, 56]).

In terms of how more vulnerable groups might view the EUC at the individual psychological level, we see a potential role for the "affect heuristic" [57]. The affect heuristic refers to the idea that although in actuarial terms the benefits and risks of an opportunity tend to be positively related ("no risk, no gain"), in many people's minds they tend to be negatively associated. This is in part driven by a desire for internal cognitive consistency and avoidance of the mental dissonance aroused by having to evaluate something as both 'good' and 'bad' at the same time [58]. For example, if an individual can see the direct benefits of a new PFAS-containing product to them personally, they are likely to downplay the related risks. Similarly, for vulnerable or disadvantaged individuals for whom the risks may loom larger, they may tend to attribute fewer potential benefits to the same product. Confusion and conflict can occur precisely because both groups are susceptible to the same bias, but because they start from a different initial focus of attention (benefits or risks), they may find it hard to understand the "other side's" perspective. The result is that both sides may see the others, to some extent correctly, as "irrational" without realising that they share the same underlying mental bias. If PFAS exemptions are given for products and processes deemed to be critical for the "functioning of society" by only one section of society, most probably those for whom the benefits loom large, serious inequities may be "built-in" unless alternative starting points and perspectives are also systematically considered.

Variation in essentiality ratings The first piece of work to more widely examine public perceptions of essentiality found significant variation in what people rated as essential or non-essential, as well as some variation across countries in Europe [11]. This highlights the need for further analysis of the concept, and the collection of what can be broadly classified as *social data* to understand the societal needs and values that ultimately determine desire for products and services related to PFAS. This observation is not new. Following extensive documentation of the failures to respond appropriately to 12 early warnings (including asbestos, polychlorinated biphenyls and anti-fouling tributyltin), the EEA's first Late Lessons report [19] also concluded that, in addition to avoiding "paralysis by analysis", risk regulators needed to:

> *"8. Ensure use of 'lay' and local knowledge, as well as relevant specialist expertise in the appraisal… [and]… 9. Take full account of the assumptions and values of different social groups" (p.169).*

Sadly, the adoption of this advice has been slow to materialise. Some 12 years later, the EEA's second Late Lessons report [20] included several case studies of known risks from chemicals such as Bisphenol A, Vinyl chloride and Perchloroethylene (aka Tetrachloroethylene). Echoing the earlier report, it continued to identify a greater need to "*foster cooperation between business, government and citizens….*" [and that] governments and businesses could collaborate more with citizens and civil society by "*disclosing and analysing the potential value conflicts entailed in acting on early warning signals*" (p.678). Both Late Lessons reports [19, 20] found significant evidence of expert hubris and "group-think" with respect to these issues, resulting in poorer chemical management. Such concurrence seeking by decision-making groups (termed 'group-think') by Janis [59] is problematic as it may suppress voices which disagree with the overall concurrence, increase the stereotyping of outgroups (i.e., here, non-experts), and ultimately override any realistic appraisal of alternative options.

Essentiality changes over time Not only can perceptions of essentiality differ by person and by country or region [11], what is broadly understood as essential may also change over time. Cousins et al. [60] give the example of Personal Protective Equipment (PPE) during the COVID-19 pandemic, when there was greater use of PFAS-containing PPE than prior to the pandemic because it was deemed that the clear and immediate benefits of better performing PPE outweighed the longer-term risks (i.e., of increased PFAS emissions related to their production, use and disposal). Also, perceptions of such issues across different groups and societies may change at different rates, or much slower than is necessary to effectively tackle emerging threats (e.g., in climate change, and chemical pollution more broadly).

Economic considerations Economic factors, often thought of but not limited to issues of market opportunity, are particularly important for business and industry stakeholders. Perceived essentiality among these actors may be strongly driven by profit margins, and a focus on short-term profit may limit some industry's ability to meet pro-environmental targets [125]. Discussing the negative impacts of products such as fossil fuels, tobacco, alcohol, and ultra-processed foods, the medical field has recently termed the prioritizing of profit over health and environmental concerns as the "commercial determinants of health" (or CDOH) [126]. In addition, industry may utilise psychology principles in marketing to ensure consumption and demand of products which can be detrimental to health and environment, including practices such as increased outlets and density of marketing for certain products (e.g., of alcohol and tobacco; [61, 62]). Relating back to considerations of fairness, these practices can act upon and increase inequalities, for example in specific geographic areas (e.g., in access to healthy or unhealthy foods; [63]), towards specific subgroups by ethnicity (e.g., advertisement targeting of Black and Hispanic youth in USA; [64]), gender (e.g., 'pink-washing'; [65]) and vulnerability, such as the targeting of children (e.g., using 'Joe Camel' as a mascot for Camel tobacco; [66]).

Given the continued use of PFAS despite solid evidence of their negative impacts [67], perhaps the CDOH framework applies here too, with evidence of lobbying, some selective research findings [14, 68], and a focus on the positive economic benefits of PFAS over the negatives [69]. As such, economic factors may be one of the largest barriers faced in successfully implementing the EUC. However, public opinion as well as consumer, voter and investor preferences are strong drivers of industry and policy-maker behaviour [70], including with respect to PFAS [71, 72]. Consequently, widespread societal support for the EUC and a societal basis for the EUC criteria could increase its attractiveness to regulators and industry. By contrast, failure to appropriately engage societal stakeholders may lead to reactance and active campaigns against the introduction of the EUC. This may be especially true if people feel they have had little say in the regulations that restrict their access to certain goods or products (e.g., as sometimes seen in the context of "green innovation") [73].

Using social and behavioural science to bridge the gap in the EUC

The central argument of this paper is that a question such as "is this essential?" requires the integration of different societal perspectives, something which appears to be currently missing from, or is at least underexplored, in the EUC to date. We posit that this lack of social engagement and resulting social data is a key reason why there seems to have been difficulty in implementing essential use in practice. In this section, we provide a research agenda aimed at highlighting how the necessary social data can be collected and integrated to better define and implement the EUC. Of course, society is not homogenous and social and behavioural scientists tend to talk of several publics, rather than one public [74]. A research chemist may be a globally respected scientist, a consultant for a multi-national chemical company, a member of a political party as well as an ethnic minority group, a parent, and live in an area where PFAS emissions are high. All of these different identities may influence their perspectives on the EUC, and value judgments with respect to whether any potential use or exemption is "necessary for health and safety" or "critical for the functioning of society" are likely to cut across not just groups but also personal identities.

The social and behavioural sciences offer different methods for data collection and analysis. In this paper, we will focus on a particularly relevant multi-method behavioural science framework for collecting and using social data in the risk context, termed the Mental Models Approach to Risk Communication (MMARC) [75].[8] We discuss the steps of the MMARC in more detail in the following section, but broadly speaking this approach builds models of how experts and non-experts think about a given issue (here, PFAS or essentiality) which help to identify overlaps and differences between groups, and from which best practice communications (e.g., for the public) can be developed to foster understanding and engagement. Example topics where the MMARC approach has been used include genetically modified organisms (GMOs) [76], electro-magnetic fields (EMFs) [77], occupational chemical exposure [78], seafood contamination [79] and microplastics [80]. One important aspect of the MMARC approach for current purposes is that in many cases it has been applied to whole classes of substances, technologies or processes such as GMO and EMFs rather than, or at least alongside, specific exemplars as in a traditional risk-management "case-by-case" approach. In this sense it can therefore be used to inform multiple, related potential "exception" cases, given the unfeasibility of trying to coordinate this for every single use case. The MMARC acknowledges that finer grained details of each specific case will be difficult for members of broader society to focus on, given their many other demands and limited technical expertise, and therefore it would be well suited to exploring public perceptions of broader classes of essential use exemptions. The methodological approach can be summarised in terms of three core phases (see Fig. 1 for an overview).

[8] We explain this approach in more detail in the following section, but broadly speaking mental models aim to reflect expert and non-experts ways of thinking about a given issue, and "*typically reflect a mix of factual knowledge, erroneous assumptions, value judgements, and uncertainty*" [76].

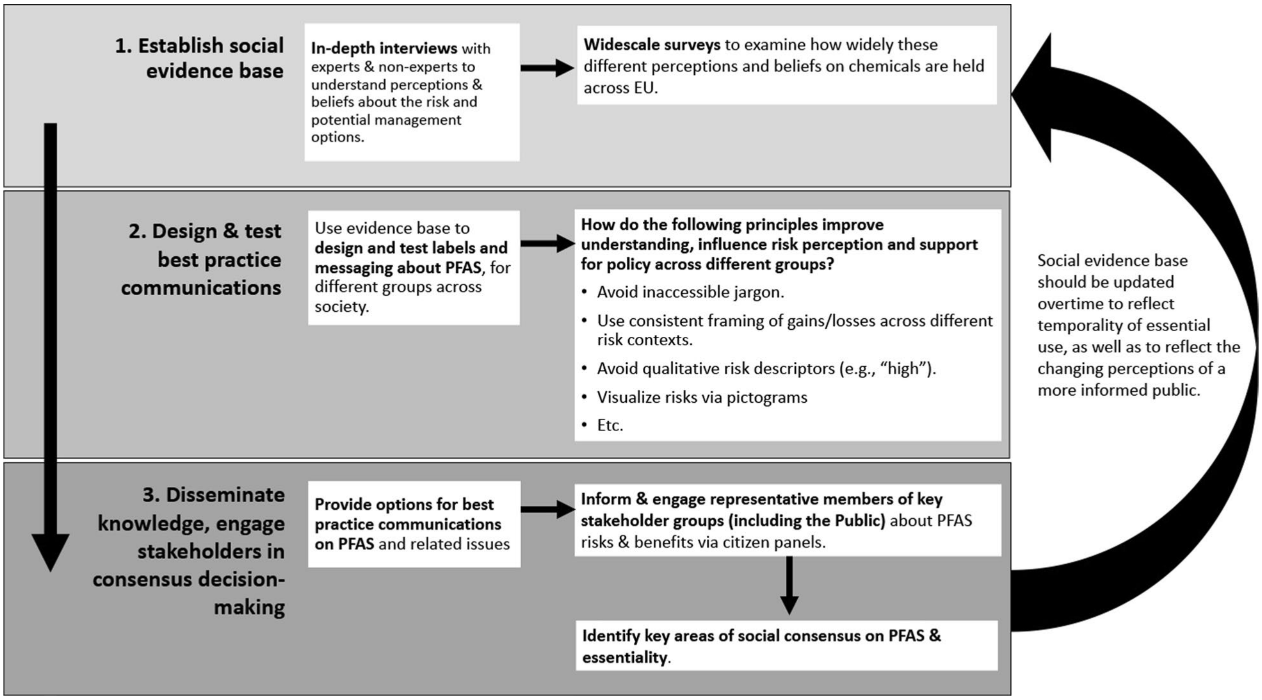


Fig. 1 Example 3-step protocol of social science methods relevant to understanding societal perceptions of PFAS and essentiality, adapted from Morgan et al. [75]

Phase 1: establish social evidence base

In the first stage of the MMARC approach, qualitative and quantitative social data are collected to develop an evidence base of what different groups in society (including experts & non-experts) know about a given hazard, their perceptions of associated risks and benefits, what sorts of issues related to the hazard they are concerned about, and their willingness to take or support different kinds of actions to mitigate any risks, including support for different policies. In the extended version we propose here, different publics would also be asked about their thoughts of essentiality and related issues.

Qualitative data The MMARC approach begins with in-depth interviews with key stakeholders, including scientists, policy makers, industry stakeholders and members of the public from a range of backgrounds to ascertain how people think about hazards and their potential risks and benefits [75, 79]. Qualitative work focuses on smaller samples with a more intense form of data collection per participant (e.g., via interviews, focus groups and observational studies [81]). In interviews, researchers can structure a discussion with the participant to cover key topics related to the central issue (e.g., perceptions of chemicals in everyday items, and how critically important or not they feel these products are to them). However, the 'strictness' of this structure can vary, such that participants may bring up new points or topics that the interview had not previously accounted for. In this way, qualitative methods have the advantage of allowing for greater discovery of factors involved in different people's reasoning about issues like chemicals, e.g., their perceived risks and benefits, as well as trade-offs, such as where people think the benefits outweigh the risks of using chemicals in certain use contexts and why, and whether certain use cases might be deemed "essential" or not. Researchers may analyse interview transcripts (i.e., a recording of everything discussed by each participant) through a top-down (inductive), bottom-up (deductive), or mixed approach, "coding" data for themes like overlaps versus differences across different groups, such as where concern may be greater for certain instances of chemical uses for non-experts, compared to experts, and why. These codes of key topics and themes can then be corroborated by additional researchers (e.g., through methods to measure inter-rater reliability; [82]).

Interviews with non-expert and expert representatives are used to build two sets of "mental model" which "*typically reflect a mix of factual knowledge, erroneous assumptions, value judgements, and uncertainty*" [76]. The combined "expert" mental model (or "inference diagram") aims to represent the current state of knowledge in experts, and contains less (but not zero) uncertainty than does the combined non-expert's mental model. Where critical gaps and uncertainties are identified in the public's model these may be targeted with specifically developed knowledge communication strategies [75]. However, since "value judgments" are intrinsically linked to views about risks, benefits and essentiality, it is also assumed that non-expert models contribute important aspects in this respect. For example, Banwell et al.'s qualitative work [83] on the perceptions of people living on PFAS-contaminated land in Australia engages with First Nations peoples and ensures that their perceptions and beliefs are described alongside those of majority communities. This qualitative work revealed that, due to their belief system focusing on the importance of a person's ties to the land, the First Nations people were less likely than other communities to be willing to leave land contaminated by PFAS. Thus, when trying to come up with solutions to PFAS more generally, considering the perceptions of diverse groups (as well as why these perceptions are held) will be paramount to fairness and equity.

Prior work on environmental issues (e.g., chemicals in food) [84] has demonstrated that there is often disagreement between experts and non-experts, and we should expect this to also be the case for PFAS and essential use. Social data collected and applied through such methods is particularly crucial since the "*social experience of risk is not confined to the technical definition of risk*" (p. 154) [85]: that is, non-experts approach risk differently from experts who use scientific risk analysis. For example, a scientist who is well informed about the emissions and physicochemical properties of PFAS may make judgments regarding risk based mainly on the severity and probability of its possible negative outcomes, which will be grounded in assessments of properties such as its persistence, mobility, bioaccumulation and toxicity, i.e., PBT and/or PMT substance properties [86] as well as its use and emission pattern. In contrast, non-experts (e.g., members of the public) incorporate social, cultural and psychological factors, such as voluntariness (i.e., to what extent do individuals choose to be exposed), novelty (i.e., how old/familiar are these sources of risk), and equity (i.e., who will be most affected by the risk and are they from a vulnerable group, such as children) into their judgments; equating to a more holistic approach to judgement, see also "risk as feelings" [87, 88].

Again, however, decision makers should not discount public perceptions of risk as "irrational" simply because they include additional psychological factors in their decision making. Moreover, as noted above, everyone can be susceptible to the "affect heuristic" and care needs to be taken to recognise this among all parties. This becomes clear in those cases where non-experts *are actually more accurate* than experts at predicting key outcomes, such as public behaviour in the face of risk (e.g., a mega-study which explored which methods of increasing vaccination uptake were most effective found that non-experts were better able to predict effectiveness, than were experts) [89]. As aforementioned, it was also "non-experts" in local communities who detected and flagged health and environmental issues related to PFAS pollution in the US, e.g., [55]. In particular, and because of such cases, applying 'deficit-framing' to non-experts is deeply flawed, where it is envisaged that information must flow in a one-directional, top-down approach from experts to non-experts.

Quantitative data Although interviews provide rich insights into how people think about complex issues, such as when and why the use of PFAS may still be essential, they are time-consuming and high in effort and are generally only conducted with relatively small samples. This makes it hard to know how representative any "*assumptions, value judgements, and uncertainty*" are in the wider population [76]. For this reason, the insights gathered from the interview-based mental models are then included in large-scale quantitative, preferably representative, social surveys that allow researchers to probe similar issues across a range of social groups, regions and countries.[9] Such surveys can also be "stratified", wherein a given population is broken into representative groups (e.g., by age and gender, as well as other variables of importance), called strata, and then a sample is drawn independently from each [90]. In addition, surveys can collect data on the same issues with the same (or similar) groups longitudinally over time (i.e., cohort or repeat-cross-sectional designs), to allow researchers to track how awareness of and concerns about certain issues evolve over time.

For example, some psychology research has found general misgivings about chemicals among the public, amounting to a generic "chemophobia" (although this refers more specifically to chemicals deemed as 'synthetic' by non-experts) [91]. Further, large representative multi-country surveys such as the Eurobarometer have been used to explore public attitudes towards chemicals in general, showing that concern is, for example, generally higher in older vs. younger adults, and in southern vs. northern European countries [92]. One possibility is to use such existing studies, which regularly call for proposals of new questions exploring current topics of policy interest, to explore European-wide perceptions of the PFAS risk and the EUC in general and/or one or two use cases in particular (e.g., water-repellent applications in medical vs. sport/leisure products). Large-scale data that enables us to understand regional perspectives may be particularly key for an issue such as the negative effects of PFAS on health and environment, since different regions could be subject to differing amounts and types of PFAS exposure and information, and are unlikely to share identical views on which uses

[9] We note that quantitative data can also be collected via other methods than just "bespoke" surveys, such as through big data approaches which can use existing data, such as large-scale databases (e.g., medical records, speech transcripts, and even visual data such as photographs), as well as data that which can be scraped from social media sites (73) or readily observed through consumer behaviour [73].

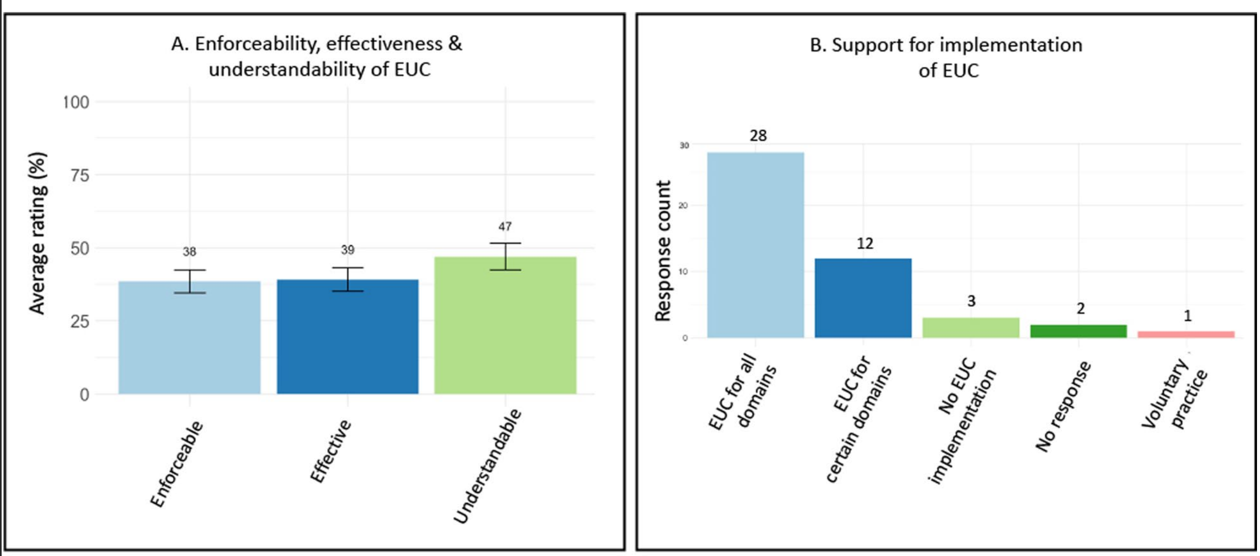
are "essential" [11, 93]. In addition, such quantitative methods can track how quickly awareness and concern about PFAS grow, as well as to track how this affects support for policies which may regulate PFAS use more strictly (e.g., in relation to the different sundown periods for PFAS proposed in the restriction proposal [48]).

Finally, we note that such methods of data collection are also useful for understanding experts, as well as so-called non-experts. In Box 1[10], we demonstrate how quantitative data can be used to examine overlap and disagreement in expert perceptions of the EUC, which can help to foster further discussion on how the defining criteria of the EUC may be improved.

Box 1: Example of how quantitative data can be used to understand expert perceptions of the EUC

We illustrate the views of 46 PFAS experts on the EUC: Experts rated (from "not at all" [0%] to "extremely" [100%]) how enforceable, effective and understandable they found the current definition of the EUC (Panel A). The concept's understandability was on average rated at only 47%, with even lower average ratings for effectiveness or enforceability. The error bars reflect differing opinions even among our expert group. Here, more than half of experts felt that the EUC was not particularly understandable. This is perhaps not particularly surprising: the EUC includes elements such as "essential for the functioning of society" and there is no inherent reason why, e.g., chemical experts should understand what this means. These results are important for our core message about the need to build social consensus.

Experts also voted for their preferred implementation of the EUC (Panel B). Despite expressing concerns about the definition of the EUC, most experts expressed strong support for implementation, with application of the EUC across all domains receiving the majority of votes (28/46 responses). Traditional psychological models demonstrate that perceived efficacy (e.g., effectiveness & enforceability) is a necessary component for behavioural intentions [116], but here we see support for an intervention despite a perceived lack of efficacy. Taken in isolation this might lead to a misunderstanding of expert opinion on the EUC. Similar methods can be used to collect data on the public's understanding of the EUC. This example uses just one step of the MMARC, and is by no means a representative sample of all relevant experts so we do not want to overstate these findings. Rather, we draw attention to how social data can be utilized with both experts and non-experts.



^Response scale: 'Not at all' (0) – 'Extremely' (100). Errors bars represent standard error.

^Count data (out of 46 respondents).

[10] Ratings were collected from the ZeroPM Prevention Workshop held in Gothenburg, Sweden in February, 2023 (Male = 20; Female = 19; Prefer not to say = 7). The majority of these experts reported belonging to purely the Academic sector (N = 20), while the rest came from Regulation, the Water sector, the Chemical sector, NGOs or Other backgrounds. Data available: https://zenodo.org/records/10462738.

Phase 2: design and test best practice communications

With a better understanding of what different stakeholder groups know and think about PFAS and potential essential use exemption cases by using the methods above, the second phase should then develop "best practice" communications to foster greater understanding and engagement [94]. Best practice risk and benefit communication principles can help a wider range of people to better interpret risks and benefits of complex issues (such as PFAS and the EUC) and to better engage with discussions on what should be done in terms of measures and policies (as in Phase 3).

With better communications, we can foster discussion between different groups [95]. For example, some experts [8] believe that the persistence of chemicals alone is enough to warrant regulation of those substances, since the amount of the substance in the environment and the doses people, animals and other organisms are exposed to will continually increase over time if action to limit emissions is not taken. However, other experts argue that persistence provides greater durability to products, which may in turn reduce emissions by allowing a given product to be used for a longer duration, e.g., before disposal and/or recycling at end-of-life [96]. What do non-expert stakeholders think about this and other matters where there is no overarching consensus among experts? Currently, we do not know of any data directly investigating how non-experts interpret chemical properties like persistence and mobility, let alone how they view the risks and benefits of substances and/or products that can include these properties. Yet knowing this information may be crucial in developing communications that adequately explain such concepts to different groups in society and allow them to join the discussion.

Ways of improving the accessibility of such communications include but are not limited to: avoiding inaccessible jargon [97], using consistent framing of gains/losses across different kinds of risk [98]; avoiding qualitative risk descriptors (e.g., "*high*") which can be interpreted in different ways [99], and visualizing risks via pictograms [100]. Better communication not only helps non-experts to better understand the risks and benefits of a given situation, but also allows them to engage in behaviours that may reduce their risk exposure (e.g., in communicating genetic risk to patients) [101]. In addition, Saleh et al. [102] have demonstrated that relevance to the audience is a key factor in making communications effective: thus, it is also important to try and better understand what kinds of information about risk people consider important and how it relates to their current values and concerns.

Psychological research has also shown that the sources and media used in communications about risk (and possibly also essentiality, though this has yet to be explored) may affect perceptions and effectiveness. Greater trust is associated with communication sources that are perceived as expert, knowledgeable, unbiased, have no vested interest in the risk and are also not seeking to sensationalise the risk [103]. The type of media conveying a message can also affect perceptions: for example, if media outlets like newspapers report on a risk before government does, risk amplification or attenuation may occur due to the way the risk is reported (which in itself can be influenced by the perceptions and aims of a given journalist; [104]). Thus, those communicating risk should consider how factors like trust (or lack thereof) in the source, or the way in which the message is communicated, can affect people's perceptions of and engagement with such issues. Finally, another benefit of utilizing a best practice communication protocol is that we can systematically test the accessibility and effectiveness of these communication materials [105], to further improve future communications and work towards acceptable regulations and solutions.

In Sect. "Background, key concepts and challenges" ('Essentiality changes over time"), we noted that perceptions of issues across different groups and societies may change at different rates, or much slower than is necessary to tackle a given issue. In psychology, this is referred to as the "status quo" bias (also called the 'default bias'; [106]) and it describes how many people will reject change (e.g., in regulation) simply because they favour existing and longstanding conditions [107]. Luckily, psychological research has also investigated ways to help overcome such bias: e.g., in the case of climate change, Rabaa et al. [106] suggest the need for greater information and education in an accessible format and to a wide audience, the teaching of climate science in schools, the demonstration of influential figures' climate-friendly behaviour changes to audiences, and easily accessible tools that allow people to compare their climate-friendly behaviours with others (e.g., the WWF's carbon footprint calculator: https://footprint.wwf.org.uk). In addition, clear labelling of consumer products is another way of communicating risks and benefits and gives people information when making purchasing decisions. A large literature on warning and other labels exists in the health and environment context, which has tested effects on cognition and behaviour (e.g., tobacco and alcohol consumption, [108]; carbon labels in the context of green food choices [109]; reduction of plastic waste [110]). These kinds of strategies should also be applied to communications about PFAS to increase support for regulation and to promote behaviour change that ultimately helps reduce PFAS consumption.

Phase 3: disseminate knowledge, engage stakeholders in consensus decision-making

Finally, best practice communications should be implemented to engage different sectors in society in the discussion of, and decision-making with respect to any risks, taking into account potential benefits foregone from specific regulatory actions. This should not be a one-way, "deficit"-based conversation: best practice communications should be used to inform and encourage genuine exchange and discussion between stakeholders. Data could then be collected in a cyclical manner, to record how society's views transform with better engagement on issues like PFAS and essentiality (e.g., as in Fig. 1). As discussed below, increased public awareness through such engagement may be key in changing industry practices and driving investment away harmful substances, thus, helping to overcome one of the economic obstacles in successfully implementing the EUC.

In the course of procedural justice[11], public participation is particularly important in cases where there is disagreement between experts and non-experts: not only can participation improve the fairness of outcomes [113, 114], decision-making which involves non-expert participants can increase the perceived legitimacy of the process, such that participants are more likely to accept the assessment or decision process as having conformed to standards of sound analysis and decision making, even if they did not agree with the final assessment or recommendation for action (e.g., to accept an expert judgment that a specific use of PFAS is necessary for the time being [115]). While the important role of public perceptions and involvement is sometimes questioned as 'non-expert', it is clear that including information from the public improves decision-making in most cases [116].

Citizens panels In an ideal world we have engagement and interactions between different stakeholder groups at many timepoints of substance regulation (as is becoming standard practice in climate action [117]). An intense method of engagement is so-called "citizen panels": based upon a jury model, this method aims to improve direct citizen participation in policy decisions, including governmental ones [118, 119]. These panels work by recruiting citizens, typically in the numbers ranging from 100 to 1000s of panellists, to collect views and insights from a representative sample of a given region, nation or collection of countries, and then by providing these citizens with expert insight on a given issue relevant to policy making. Panel participants study a problem, discuss issues, and then reach some form of consensus on the problem [120]. Such panels have already been applied to several environmental issues, including local environmental risks, including chemical accidents and the subsequent contamination of land [121], and the meeting of national climate targets for CO_2 reductions [122].

Finally, effectively engaging with wider society about PFAS risks may be paramount in solving one of the economic hurdles involved with PFAS: with increasing public awareness of PFAS, comes issues of who pays for pollution, as well as investor liability for associating with potential polluters. In 2022, for instance, investors with $8 trillion in assets called for a phase-out of dangerous chemicals by industry, including PFAS, showing that the continued use of dangerous chemicals may harm industry through reduced investments [3]. One of the underlying reasons why investors are calling for a move away from dangerous chemicals is the principle of "extended producer responsibility" (EPR) and the fear of future liability, especially for health impacts [123]. Thus, ensuring effective dialogue between consumers, industry and investors (e.g., via methods like citizen panels) may be paramount in demonstrating support for EPR practices and thus a shift away from PFAS use. In other environmental domains, e.g., climate change and plastic pollution, legal cases are already being brought to the courts that argue that governments or companies are responsible for damages [124, 125].

The necessity of social data within the EUC framework

Building on the discussion above, we see social data and insights gathered from social and behavioural science approaches as a crucial element for the EUC framework (as proposed by Bougas et al. [49]), and we see various stages where the application of social data will be particularly helpful under this framework (see Fig. 2). Firstly, in even deciding what makes a use essential the main argument of this paper is that a wider range of voices, especially the public, need to be included. Secondly, in the case that a use is deemed essential, social data offers us further insight into different kinds of alternatives and their acceptability to different audiences. For example, social data (e.g., from interviews or surveys) can be particularly useful in cases where no suitable technical or economic alternative is yet available. In such cases, the collection of such data may lead to cases of "social substitution", wherein substances can be phased out even without alternatives that are matched in performance or price because we have evidence that the majority of society will support this; an example of this is this is the ban of PFAS in high performance ski waxes [126]. In addition, representatives from the public can engage in the discussion on the issue (via citizen panels) and help determine where use of PFAS substances should be maintained

[11] While there is debate on the effectiveness of public participation in decision-making, with plenty discussion of both its strengths and limitations, e.g., [111, 112], the authors, as scientists in public service, see citizen participation in decision making as a necessary component for the legitimacy of democracy. Thus, we focus on methods to collect and utilise data that promotes such public participation in decision-making.

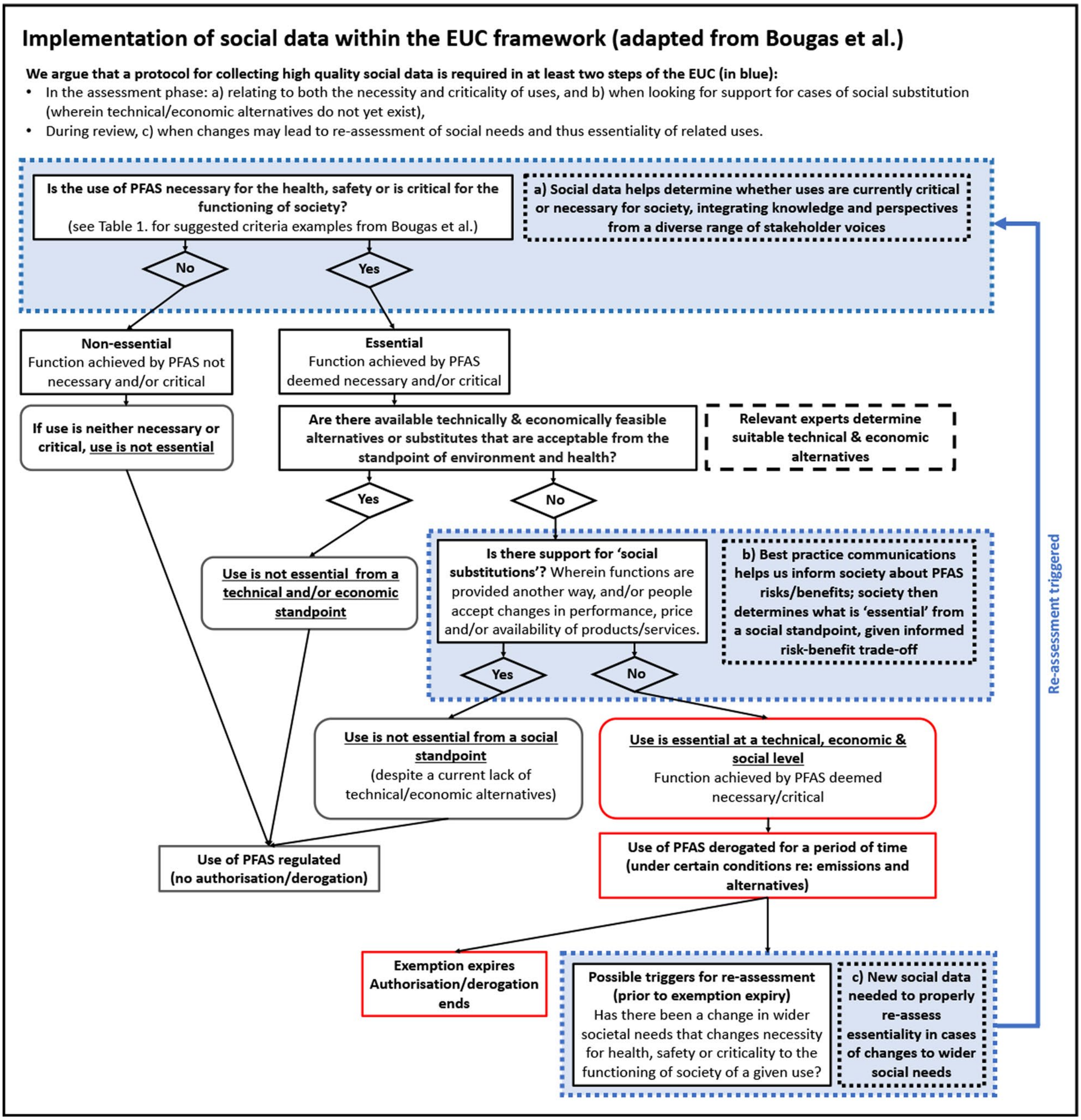


Fig. 2 Example of how social data can be used to support the application of the EUC. This flowchart is adapted from the original proposed by Bougas et al. [49]

or stopped. Finally, since the process outlined in Fig. 2 maintains its dynamic nature, the authorisation/derogation of a product as essential can be re-assessed, given changes in alternative technologies and societal needs at a given time. Particularly in the latter case, the inclusion of wider social data will be paramount when reviewing what is essential to society.

Indeed, there may be further steps in which social data can better inform the decision-making process, but here we outline three stages already where its inclusion is beneficial to ensuring a wider range of perspectives are heard and acted upon, as well as potentially leading to additional cases for the removal of harmful chemicals via social substitution. We also note that, while we split substitution into "technical" and "social" levels in Fig. 2, in reality both are heavily intertwined. Deciding if a technical substitute is "good enough" will also often warrant social aspects, such as "will this product still perform to the level needed/expected by your average consumer in a given society?".

Method limitations

We note that with any of the methods we discuss in this section, some people may not be willing or feel comfortable enough to disclose their beliefs in certain settings. There is no perfect solution to these kinds of issues, but the methods outlined above can be used and adapted to encourage different kinds of voices to be heard. For example, some people may not be willing to speak out in large stakeholder workshops, instead smaller groups or even 1-on-1 interviews (as outlined above) can be conducted, to allow each person the space to speak out [116]. In particular, minority groups may not feel comfortable talking with members from majority or perceived outgroups. As such, steps should be taken to find a mediator to allow such conversations to happen (e.g., as in Banwell et al.'s work engaging with First Nations communities living on PFAS-contaminated land [83]).

It is also important to note also the relative imbalance of power members of the public may be perceived as having, compared to experts like large chemical industries. However, other cases on environmental risks demonstrate that public support can trigger policy support, foster industry cooperation and shift innovation towards alternatives, even where the human health risk of a potential pollutant is unclear, e.g., in the case of microplastics [127], by demonstrating that well-informed consumer bases have a preference for "greener", more environmentally friendly products [71, 128, 129]. In the case of PFAS, Holmquist et al. [71] demonstrated that when consumers were given more specific information about the health risks associated with exposure to PFAS, they expressed greater willingness to pay for outdoor garments that did not contain them[12]. Similarly, in the case of plastic microbeads, Dauvergne [130] talks about the "power of environmental norms" in which increased public concern about microbeads in rinse-off products helped drive voluntary phase-outs of their usage by industry. Indeed, in the case of plastics more generally, we see increasing public concern going "hand-in-hand" with increased political attention to the issue of plastic pollution (particularly, marine plastic pollution), with the intention of many governments to reduce plastic pollution by eliminating single use plastics [131]. Thus, despite these imbalances in power and access to information, the public can still be a huge force for change in protecting human and environmental health.

Another issue is that these methods require substantial and sufficient resources to be implemented well. But the costs of not addressing the problems without societal consensus are likely to be orders of magnitude higher. As noted above, the costs of not mitigating PFAS contamination at a single airport were estimated at approximately $670,000 per year [38]. Systematically using best practice social science data collection, communication and engagement approaches in tandem with technical innovation and input from technical experts is what is ultimately required to support a more citizen-informed social consensus that will result in more widely accepted regulatory approaches. Because of this wider acceptance, such multi-faceted approaches are likely to prove to be cost-effective in the long-term. Reliance on expert judgment alone is likely to be cheaper in the short-term but could be far more costly, in terms of population and environmental health, in the long-term [19, 20].

Finally, at this early stage, we can see a role for the social and behavioural sciences both in terms of engaging the public with the whole idea of the EUC (is it understood, how is it received?), and also for more specific potential exemptions based on considerations of what might be critical for the functioning of society. We recognise, however, that it is clearly unfeasible to engage in such extensive efforts for each and every specific exemption case, just as a case-by-case, risk-based approach is already unfeasible for all PFAS substances. It was precisely for this reason why we looked to the MMARC approach as a guiding framework, given that it outlines the steps needed to engage non-expert publics with generic risk issues rather than specific use cases, for example, to understand their risk perceptions of genetically modified crops in general, rather than say, a specific "gene-altered" tomato. Precisely how the MMARC approach could best be applied to the essentiality of PFAS is in development and is likely to change as new insights are uncovered. The current paper is fundamentally a call for this process to start, rather than a statement of exactly what needs to be done.

Conclusion

The EUC is promising but faces a range of challenges, particularly in designating which uses and functions of PFAS are "necessary for health and/or safety" or "critical for the functioning of society" and why, because such judgements are far more than technical in nature and require an understanding of societal values and consensus. The EEA's "Late lessons from early warnings" reports already demonstrated that not adequately considering the possible limitations and disagreements among expert

[12] Greater willingness-to-pay for alternatives was measured as a '0%', '10%' or '50%' price increase from whatever baseline price a participant would be willing to pay for a garment containing fluorinated substances.

views, and failing to include views and assumptions from different non-expert groups, can lead to regrettable outcomes for both human health and the environment [19, 20]. Overcoming these challenges requires the integration of social and behavioural science, and the establishment of a new social evidence base regarding the benefits and risks of PFAS, as well as the essentiality of its different uses and the technical functions it serves in different products. From here, we can design and test communications for specific groups, to inform them about PFAS, and to allow them to better engage in discussion and decision-making regarding PFAS and its essential uses. This data can also better inform labelling options and proposals, such as the digital product passport [132], and help us predict which regulation and policies different groups will support or oppose. The development of a broad social consensus on PFAS and essentiality is therefore paramount, if we are to sustainably reduce PFAS pollution and its associated impacts on the environment and human health. We hope the current article succeeds in providing an initial, tentative research agenda for the social and behavioural sciences for how such research might proceed.

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Author contributions
All authors contributed to drafting, writing and revising the manuscript, as well as approving the submitted version and are accountable for their own contributions and accuracy.

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Availability of data and materials
Expert data shown in Box 1 are available at: https://zenodo.org/records/10462738.

Declarations

Ethics approval and consent to participate
This project was approved by University of Vienna Ethics Committee. Expert participants consented to take part in the survey on EUC as part of the 2023 ZeroPM Prevention workshop.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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