Additive Sustainability Footprint: Rationale and Pilot Evaluation of a Tool for Assessing the Sustainable Use of PVC Additives

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PVC compounds contain additives necessary for processing and stability, and to modify the plastic’s properties. The Europe-wide VinylPlus® voluntary commitment includes a challenge to make progress toward sustainable use of additives. Additive Sustainability Footprint (ASF) was developed to assess sustainable use of additives across the whole societal life cycles of finished PVC articles, taking a risk-based approach rather than simplistic hazard assessment. ASF addresses impacts across six life cycle assessment (LCA) stages established by ISO Standard 14040, using the four System Conditions (sustainability principles) developed by The Natural Step (TNS) covering social as well as environmental factors. For each LCA stage/System Condition combination, seven generically similar questions cover negative impacts (many covered by existing tools and regulations) but also the additive’s positive contributions to the sustainability of finished articles. Positive contributions include ethical sourcing, longevity of service life, low maintenance inputs, and recyclability. Answers to questions determine a score, which can be combined across the life cycle and with other additives. Testing on a generic EU PVC window profile supported ASF development and demonstrated applicability and potential benefits including use for sensitivity analysis of alternative additives from different geopolitical regions or from recycled as opposed to virgin sources. J. VINYL ADDIT. TECHNOL., 26:196–208, 2020. © 2019 The Authors. Journal of Vinyl and Additive Technology published by Wiley Periodicals, Inc. on behalf of Society of Plastics Engineers.

INTRODUCTION

Schemes for assessment of chemical sustainability differ significantly in definitions of objective, interpretation, and scope, many focusing on intrinsic chemical properties and particularly potential hazard [1]. Regulatory mechanisms and management tools commonly focus purely on hazard reduction or elimination to secure environmental and human health, including the EU REACH [2] “Substances of Very High Concern”/“Candidate List,” EU Waste Framework Directive [3], the 12 principles of Green Chemistry [4] and GreenScreen® [5]. Though serving some useful purposes, hazard-based classifications, such as that within EU REACH, overlook actual risks to human health or the environment when substances are included in products, potentially leading to undesirable consequences such as restrictions on use of safe products, substitution toward less safe products and disincentives to innovate [6].

Risk assessment integrates hazard with potential exposure [7], contextualizing assessment into use of the chemical. A risk-based assessment can, for example, link inherent chemical properties to acceptable dose, based on likelihood and severity of exposure. Even when classified as hazardous, the way in which a substance is deployed can justify acceptable (authorized) uses (REACH Art. 60, paragraph 2). For example, some potentially hazardous substances may be wholly consumed in enclosed technical production processes, or bonded in immobile forms within final products. This has significant implications for the potential for safe management of risks in specific contexts.

Both hazard and risk approaches founded largely on intrinsic chemical attributes also fail to account for, or else inconsistently address, wider sustainability issues related to sourcing, production, and application of chemicals, their interaction with products within which they may be used and their fate at or beyond end-of-life. It is increasingly recognized that a more holistic approach to the use and stewardship of chemicals throughout their entire societal life cycles is essential. For example, the term “sustainable chemistry”, as distinct from “green chemistry” and “operational safe use” criteria [8], has been proposed by the German Federal Environment Agency [9] to address increased resource efficiency, safer and less polluting substances, innovations beyond sector borders, improved performance, and increased added value.

Life cycle assessment (LCA) measures some of these aspects of “sustainable chemistry”, using well-established environmental impact categories such as global warming

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potential, eutrophication, different aspects of ecotoxicity and ozone-forming potential [10]. The LCA approach is, for example, the basis for Environmental Product Declarations (EPDs) [2] and the life cycle concept is central to the “circular economy” strategy of the EU [3]. Yet models used to assess life-cycle impacts differ from each other in basic principles, scope, and outcomes, potentially omitting impacts of chemical emissions and making different approaches hard to reconcile [11]. Integration of different risk criteria into an overall LCA is a further cause of uncertainty [12]. The lack of social considerations in conventional LCA has been acknowledged as a deficiency, and the SETAC/UNEP Social LCA (S-LCA) model is working to include social impacts as a more useful tool in progress toward sustainable development [13]. Generally, if recognized, the focus has been on negative social impacts, though substances enter societal use for positive purposes too supporting a diversity of human needs, for which the UN [14] Sustainable Development Goals (SDGs) now provide a structured and consensual framing that reassert the primacy of meeting human needs in implementation of sustainable development [15].

All available assessment methods make some contribution to environmental, economic, and societal factors within the broad definition of sustainable development [16]. However, there are clear differences in the scope and hidden assumptions in each method around what is meant by “sustainable”. The lack of clarity around definitions of sustainability has been well-debated but is highly relevant to the sustainability assessment of chemicals. A proliferation of hundreds of redefinitions of sustainable development, many apparently designed to suit the priorities of their originators rather than based on robust and replicable scientific foundations, occurred within a few years of political acceptance of the concept [17]. The lack of an holistic and common frame of reference based on a precise and comprehensive definition of sustainability means that application of these various tools can create a range of problems. These include: elimination of potentially safely used chemicals or regrettable substitution on the basis of inherent chemical properties divorced from life-cycle risks; shifting the burden on the basis of improving chemistry to the detriment of other sustainability parameters (such as contribution to product durability, climate change issues, or the competitive effects of biologically based substances with food security); or competing objectives of a toxic free-environment with the need to recycle material with potentially toxic constituents in a circular economy [18]. Fragmented action based on tools lacking a coherent, scientific basis in sustainability principles can result in unsustainable or sub-optimal progress and stranded investments. Robust sustainability assessment of chemical use depends substantially on life-cycle management rather than unhelpfully simplistic judgements about “good” or “bad” substances divorced from this context [19].

Clearly, a comprehensive, science-based interpretation of sustainability is needed to deal with the complexities of chemical use throughout whole societal life cycles. A diversity of scientifically founded approaches to sustainable development relevant to materials and products has been developed, a subset of which is listed in Table 1. One such definition of sustainability is embodied in the Framework for Strategic Sustainable Development advocated by the international nonprofit organization, The Natural Step (TNS), assessed as one of the most robust models transparently founded on consensual scientific principles presented within a package of operationally relevant methods [17]. The research on its development and application over almost 30 years is described by reference [20].

Central to the TNS Framework is a science-based model of a sustainable system, from which a set of System Conditions for a sustainable society (referred to here as “TNS System Conditions”) are derived (see Table 2 with descriptions of related topics). These System Conditions serve as a set of sustainability principles to develop visions, assess current reality, and evaluate strategic improvement strategies.

The TNS Framework provides a comprehensive, scientifically founded overview of the broad dimensions of sustainability into which the specific contributions of other tools can be integrated. Previous research has used the TNS Framework to create synergy and alignment between various sustainability tools and concepts (e.g. LEAD, Factor X, Cradle to Cradle, LCA), evaluating which aspects of sustainability they cover and where additional tools are needed [31][32].

These principles were used to assess the potential of PVC to be a part of a sustainable future, based on a consensual process facilitated by TNS, supported by the Environment Agency in England and Wales [33]. Five key sustainability challenges for PVC were derived from this analysis. Through a long evolutionary process (summarized by references [34,35]), this science-based TNS approach became progressively adopted within the European PVC industry. In 2011, VinylPlus®, the voluntary commitment to sustainable development of the European PVC industry [spanning the EU-28 Member States plus Switzerland and Norway], adapted these five challenges within a voluntary commitment, with an associated set of targets up to 2020 (http://www.vinylplus.eu/, accessed 17th February 2019) [36]. Table 3 documents the original five sustainability challenges for PVC presented by reference [33], and their articulation under the VinylPlus® voluntary commitment including relevant VinylPlus® targets to 2020.

VinylPlus® Challenge 3 recognizes sustainable use of additives as a key challenge, the VinylPlus® “roadmap” for sustainability committing the European industry to use the TNS definition of a sustainable society to assess the use of additives within PVC articles (the REACH term

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**TABLE 1.** Subset examples of science-based interpretations of sustainability

- The Natural Step (TNS) Framework [21].
- The Five capitals model [22].
- The STEEP framework [23] as applied to sustainability issues by [24–27].
- The ecosystem services framework [28].
- The Ecosystem Approach [29].

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TABLE 2. The TNS System Conditions, with examples of topics to which they relate and linked success criteria used in this study

TNS System Conditions for a sustainable society (sustainability principles)

- [Explanatory note]
  - Success criteria for the sustainable use of PVC additives used in this study

In a sustainable society, nature is not subject to systematically increasing...

1. Concentrations of substances extracted from the Earth’s crust.
- [Explanation: Human activities can liberate into ecosystems substances sequestered over geological time in the lithosphere]
  - Scarc metal, minerals, and fossil carbon must not be released to nature at a rate exceeding natural reassimilation, requiring phase-out or recapture in controlled loops of scarce mined materials; and
  - Sources of raw materials (including energy) must be renewable, or the resources must be fully recycled, avoiding fossil carbon or other emissions.

2. Concentrations of substances produced by society.
- [Explanation: Substances manufactured by society and novel to nature, or modifications of additive substances but considering risk within the sustainable use of additives, accounting for intrinsic properties of additive substances but considering risk within the full societal life cycle context of the PVC articles into which they are incorporated, based on a scientific definition of sustainability [37].

3. Degradation by physical means.
- [Explanation: Physical degradation results when living or nonliving elements of ecosystems and their processes (water, land, and other resource use including ecosystem disturbance) are exploited beyond renewable limits.]
  - Sourcing of raw materials used for production of additives must come from well-managed ecosystems, and spent materials beyond end-of-life must not physically degrade ecosystems.

And in that sustainable society...

4. People are not subject to structural obstacles to health, influence, competence, impartiality, and meaning.
- [Explanation: Actions or policies that undermine the ability of people to meet their needs, including health and safety; basic rights; skills and knowledge; equity [resource efficiency / depletion]; and well-being/meaning]
  - PVC products including their additives must not lead to negative impacts on the wellbeing of humans or the environment;
  - Additives must be produced and managed under responsible and ethical practices;
  - Additives enable reliable, technical performance to deliver functionality supporting diverse human needs; and
  - Additives must not restrict the capacity for efficient management of resources through mechanical and feedstock recycling either by:
    - reduction in the quality and quantity of the recyclate; or
    - preventing mixing of PVC from multiple end-of-life and postindustrial products in recycling streams (compatibility).

Social dimensions of sustainability may be represented as a set of five distinct social sustainability principles [30].

TABLE 3. The five TNS and VinylPlus® sustainable development challenges for PVC

| PVC evaluation using The Natural Step Framework [33] | VinylPlus® voluntary commitment [36] (challenges renumbered by stakeholder priority within the VinylPlus® roadmap) |
|-----------------------------------------------------|------------------------------------------------------------------------------------------------------------|
| 1. The industry should commit itself long term to becoming carbon neutral | Challenge 4. Sustainable energy and climate stability—We will help minimize climate impacts through reducing energy and raw material use, potentially endeavoring to switch to renewable sources and promoting sustainable innovation. |
| 2. The industry should commit itself long term to a controlled-loop system of PVC waste | Challenge 1. Controlled loop management—We will work towards the more efficient use and control of PVC throughout its life cycle. |
| 3. The industry should commit itself long term to ensuring that releases of persistent organic compounds from the whole life cycle do not result in systemic increases in concentration in nature | Challenge 2. Organochlorine emissions—We will help to ensure that persistent organic compounds do not accumulate in nature and that other emissions are reduced. |
| 4. The industry should review the use of all additives consistent with attaining full sustainability, and especially commit to phasing out long-term substances that can accumulate in nature or where there is reasonable doubt regarding toxic effects | Challenge 3. Sustainable use of additives—We will review the use of PVC additives and move toward more sustainable additives systems. |
| 5. The industry should commit to the raising of awareness about sustainable development across the industry, and the inclusion of all participants in its achievement | Challenge 5. Sustainability awareness—We will continue to build sustainability awareness across the value chain—including stakeholders inside and outside the industry—to accelerate progress toward resolving our sustainability challenges. |
This article outlines the development, and assesses a pilot implementation, of Additive Sustainability Footprint (ASF): a tool developed to assess the sustainable use of additives across the societal life cycle of PVC articles. Pilot implementation on a generic PVC window profile served as a test-bed for the evolving ASF process, assessing its suitability for addressing objective sustainability principles across a full article life cycle, for operational deployment, and to highlight further development needs.

METHODS

A vision of sustainable use of additives necessarily includes their incorporation within PVC compounds and articles. One vision of sustainable use of additives is that an idealized production process for PVC producing flawless linear polymer chains requires no stabilizer additives [38]. As this is infeasible today, stabilizers constitute an essential additive type contributing to robust and useful PVC articles, conferring both significant benefits to the finished plastic but also negative impacts requiring further study and innovation.

ASF Development Began with Recognition of Four Factors

1. The European vinyl industry was already making significant investments related to aspects of sustainable development under initiatives such as REACH registration files, LCAs, EPDs, and product environmental footprints (PEFs);
2. These initiatives fail to account for the roles and behaviors of additives as functional constituents of complex products, some (e.g. REACH) relating to intrinsic chemical properties addressed in isolation while others (for example LCAs, EPD and PEF) focus on environmental impacts of production and, in some cases, of other phases of the life cycle;
3. None of these initiatives accounts for the wider, systemic context of sustainability as articulated by the four TNS System Conditions; and
4. None accounts for positive benefits arising from the functional contributions of additives in addition to their negative aspects, enabling articles to address the meeting of human needs on a potentially sustainable basis, or at least on a more sustainable basis compared to competitor materials or if the additives had been omitted from the PVC matrix. Stabilizers, impact modifiers, and pigments, for example, can contribute to the durability of compounded PVC plastic, enabling products to provide long service lives per unit of chemical and energy, resistance to fouling or contamination, and/or reducing maintenance inputs over life compared to alternatives. Many additives are also inherently recyclable within PVC material, contributing to progress toward controlled loop management and reductions in virgin inputs.

Inclusion of these positive contributions to the meeting of human needs is therefore integral to ASF and consistent with emerging global attention, particularly through the 17 UN SDGs as recognized within the VinylPlus® voluntary commitment and providing a structured and consensual framing of needs for ASF. The potential contributions of PVC to the SDGs are also used as an example by reference [15] in helping reassert the vision of sustainable development as one of meeting human needs in enduring and materially efficient ways, consistent with the seminal “Brundtland definition” of sustainable development [16], rather than as perceived constraining regulatory criteria. TNS System Condition 4 (“People must not be subject to structural obstacles to health, influence, competence, impartiality and meaning”) provides a science-based justification for integration of the meeting of needs into ASF assessment across life cycle stages, addressing both potentially negative as well as positive contributions.

A set of guiding principles was established and used to explain the evolving ASF approach to stakeholders, and to engage them in the development process. Key principles were that: sustainability assessment is not about compliance with what exists, but addresses long-term alignment and progress with principles of sustainability; “fit” with existing industry requirements, methods and investments; and alignment with LCAs, EPDs, and other methods already in use. The development process for what was to become ASF was described using a jigsaw metaphor, conceptualizing existing, more narrowly framed environmental assessments and investments as valuable “jigsaw pieces” (EPDs, REACH, LCAs, PEFs, and other tools) contributing to a broader picture of sustainability but also recognizing that there were many “missing jigsaw pieces”. Figure 1 illustrates “jigsaw pieces” contributed by EPDs which, under EN 15804, includes seven impact categories: global warming, ozone depletion, photochemical ozone formation, acidification, eutrophication, mineral and fossil resource depletion, and nonfossil resource depletion, but not parameters such as water resource depletion and toxicity to human health [39]. Figure 2 makes a similar comparison of the contributory “jigsaw pieces” provided by PEF.

The TNS Sustainability LCA tool (described below) provided a foundation for ASF development. Subsequent development progressed through four distinct phases, agreed with a VinylPlus® Additives Committee tasked with progressing VinylPlus® Challenge 3: “Sustainable use of additives”.

Phase 1: Development of Robust Criteria for Sustainable Use of Additives. In addition to the robust sustainability criteria described in the Introduction, PVC additives were defined as chemical substances added to PVC resin during processing (compounding, extrusion, calendering, molding, etc.) to support the processing step or to confer specific performances and/or cost benefits to the final PVC article. Criteria development was informed by lessons from previous application of the TNS System Condition by various companies in the PVC value chain to assess the sustainability of additives.

Phase 2: Validation of Criteria for “Sustainable Use of Additives” in Conjunction With the Downstream Value Chain. This comprised a consultation exercise on the evolving assessment methodology held in Vienna in September 2014 with stakeholders both from within but also outside the PVC industry. Wider issues of concern about PVC were expressed and debated. Specifically
regarding additives, it was agreed that assessment of their sustainability can not be separated from the rest of the life cycle and that VinylPlus® Challenge 3 for use of additives was interconnected with the other four VinylPlus® Challenges, particularly the life cycle stage postmanufacturing. The need to produce PVC from which additives, particularly endocrine disrupters, do “leak out” was recognized. Other items raised and debated were the need for adequate representation of human health and environmental impacts, taking a precautionary approach to handling lack of data and uncertainties, that the approach should guide substitution decisions, and that microplastic generation was to be considered. The general approach of harmonizing assessment of the use of additives with LCA was welcomed.

Phase 3: Choice of Pilot PVC Application and Associated Additives. This phase entailed agreement on pilot implementation of ASF on a generic EU PVC window profile, for which an EPD had already been developed. The EPD identified a range of generic additives (Ca/Zn stabilizer, acrylic impact modifier, TiO₂ pigment and CaCO₃ filler). This range was subsequently broadened for sensitivity analysis based on two alternative additives and their associated supply chains and life cycles: chlorinated polyethylene (CPE) impact modifier; and Pb stabilizer introduced into the profile as a constituent of recycled PVC.

Phase 4: Develop a Systematic Framework Methodology, Taking into Account the EU PEF Concept. The ASF development phase also included selection of an appropriate LCA methodology, mainly already described in the Introduction. [40,41] explored how incorporation of the TNS Framework can enable wider sustainability assessment when implemented within the LCA method published as ISO Standard 14040 [42] (formerly ISO 14040:1997, ISO 14041:1998, ISO 14042:2000, and ISO 14043:2000), subsequently developed by TNS into a sustainability LCA (SLCA) approach [43] [44]. SLCA addresses strategic pathways toward full sustainability based on the TNS Framework, rather than focusing on specific-known problems [40]. SLCA has been applied in various operational contexts, including for example to paints [45].

Assessing the sustainable use of additives across whole product life cycles, and consistent with the established LCA methodology, ASF is rooted in the TNS Framework and its application through the modified SLCA approach to ensure that it represents a science-based compass for innovation addressing all dimensions of sustainability. ASF/SLCA starts with an inventory of substances involved. Multiple details are required to determine likely environmental and social impacts across the full societal life cycle of PVC articles, including: additive substance chemistry and purpose; aspects of supply chains including where and how materials are
sourced and produced; and fate of articles at end-of-life including different disposal or recycling options. If any of this supply chain or other information is not known, the ASF process records this as a knowledge gap at the relevant life cycle stage, highlighting areas for subsequent information gathering as a contribution to future revision of assessment of the sustainable use of the additive.

The European Commission is developing a PEF methodology for potential application to all products on the European market [46], though at present it remains unclear when or if this methodology will be used or its application to construction products (including windows). The ASF development team was regularly briefed about progress with PEF, and progressed ASF development consistent with its perceived direction.

Structure of the ASF Tool. At the core of the ASF tool is a matrix orienting each of the TNS System Conditions against the six ISO14040 life cycle stages, central to the TNS SLCA process (illustrated in Fig. 3). Assessment within each cell is based on a list of seven generically similar questions, three of them “impact questions,” and four “progress questions”, adapted to each particular System Condition/life cycle cell. Answers comprise three elements: (1) overall response (“YES,” “NO,” “Not applicable” or “Do not know”); (2) assessment of confidence level (“HIGH” or “LOW”); and (3) comments/references documenting supporting evidence or reasoned justification for answers provided. An illustrative example is provided in Fig. 4 for LCA stage 1 (“raw materials: acquisition & pre-processing”) relating to TNS System Condition 1 (systematic accumulation of lithospheric substances) for a generic Ca/Zn stabilizer.

- The three “impact questions” relate to conflicts with TNS System Conditions. (The example in Fig. 4 addresses...
### TNS System Conditions

| System Condition | LCA life cycle stages as relevant to the sustainable use of PVC additives |
|------------------|--------------------------------------------------------------------------|
| SC1 (Earth’s crust) | Impact questions | Impact questions | Impact questions | Impact questions | Impact questions | Impact questions | Impact questions |
| SC2 (Man-made substances) | Progress questions | Progress questions | Progress questions | Progress questions | Progress questions | Progress questions | Progress questions |
| SC3 (Physical degradation) | Impact questions | Progress questions | Progress questions | Progress questions | Progress questions | Progress questions | Progress questions |
| SC4 (Human needs) | Impact questions | Progress questions | Progress questions | Progress questions | Progress questions | Progress questions | Progress questions |

**FIG. 3.** The four TNS System Conditions (SC1-4 vertically) oriented against six LCA stages for the PVC article. [Color figure can be viewed at wileyonlinelibrary.com]

System Condition 1 raw material constituents and processes likely to release substances derived from the Earth’s crust, including implications of carbon-based energy use, for Ca/Zn stabilizer at the “raw materials” stage.  
- The four “progress questions” address future commitments, such as targets in place to avoid such conflicts (including resource efficiency, responsible sourcing and filling knowledge gaps). This builds upon simple quantitative measurements of, for example, quantity of CO₂ equivalent emissions by also asking questions about the use of renewable versus fossil energy and also strategies in place to progressively decarbonize in future.

Adapted questions address all other LCA stage/System Condition combinations (24 cells each with seven questions requiring 168 responses in all). Ethical and process...
management as well as environmental dimensions are covered. The datasheet is subsequently available for review by those needing to do so, but can be password protected to preserve commercially or otherwise sensitive data (as is the case for the pilot ASF implementation).

For each cell of the TNS System Condition/LCA stage table at the core of ASF, scores are allocated on a seven-point scale according to the number of questions answered positively. Where there are knowledge gaps, the default is that the question is answered negatively, highlighting potential “sustainability blind spots” that can be improved with further information gathering (or action if unsustainable practice is disclosed). In the illustrative example in Fig. 4, the score for that additive and LCA/System Condition cell would be “1” (reflecting the single YES response in this cell for “progress question” 1.1.7). Overall assessment is presented graphically on a color-coded scale running from green (fully compliant) to red (unsustainable or information deficient) cell by cell, as represented illustratively in Fig. 5 reflecting the cyclic nature of sustainable resource use. Underpinning data behind scores allocated in each cell can be interrogated by users with appropriate access rights to identify actual or potential “unsustainability hotspots” that can subsequently form the basis for further information gathering or innovations as a contribution to progressing the sustainable use of additives.

Once completed, authors, reviewers and participants of the ASF sign a declaration verifying compliance with and completion of the ASF process acknowledging all assumptions used in the “snapshot” assessment at a given point in time.

Pilot Application of ASF. The ASF tool was applied to a generic European PVC window profile article, for which an EPD had already been published including an inventory of principal additives [47]. Selection of this subset of additives was based on extension of the REACH protocol of including any chemical substance incorporated within a mixture at a concentration above 0.3 phr (parts per hundred of PVC), above which the substance may be classified as potentially hazardous. An exception to this is for substances included in the SVHC (substance of very high concern) list, or otherwise classified as of concern, in which case the threshold reduces to 0.1%.

The ASF was applied to a subset of six potential additives to the EU generic PVC window profile: Ca/Zn stabilizer; Pb stabilizer in recycled PVC; acrylic impact modifier; CPE impact modifier; CaCO3 filler; and TiO2 pigment. As described previously, Pb stabilizer introduced in recycled PVC and CPE impact modifier were considered to enable assessment of supply chains in different geopolitical regions and sustainability contributions of resource recovery.

RESULTS

Results of ASF development include both technical assessment of the EU generic PVC window profile, but also the learning entailed in development of the ASF tool through the pilot process.

ASF development followed the ten-step SLCA approach consistent with established LCA protocols [48]:

![FIG. 5. Illustrative representation of ASF summary output highlighting compliance or deviation/information deficiencies by TNS System Condition across life cycle stages for a generic Ca/Zn stabilizer. (ASF outputs generally presented in color but rendered in greyscale for journal production purposes.) [Color figure can be viewed at wileyonlinelibrary.com]](image)
-ever, key insights emerging from its production include:

- Additives are sustainably produced using materials that are responsibly sourced.
- Additives support the sustainable management of PVC products (e.g. safe and recyclable).
- The functional benefits of additives enable PVC products to support sustainable development (e.g. meeting the UN Sustainable Goals).
- Step 2 “Creating a shared definition of the sustainable product system” entails agreement on success criteria for sustainable use of additives across each of the life-cycle stages based on TNS sustainability principles (noted in Table 2);
- Step 3 “Setting system boundaries” establishes de minimus additive concentrations and other aspects of the life cycle such as aligning with assumptions in the published EPD and other protocols used by the industry, as well as agreement on guiding principles;
- Step 4 “Inventory analysis” collects information relevant to addressing the social and environmental criteria covered by questions in Step 6;
- Step 5 “Sustainability assessment” uses the TNS System Conditions to assess sustainability strengths and weaknesses;
- Step 6 “Identify key impact areas” entails answering sustainability-relevant questions for each combination of TNS System Conditions and life-cycle stage as illustrated in Fig. 4;
- Step 7 “Brainstorm possible solutions” considers options to address “sustainability hotspots” highlighted in Step 6;
- Step 8 “Prioritize solutions” prioritizes optimal solutions to address “sustainability hotspots”;
- Step 9 “Create an innovation roadmap” entails taking innovations through to measurable actions; and
- Step 10 “Measure and report progress” includes as a useful output a summary “Snapshot report” comprising a description that an ASF has been performed, an explanation of the process of the study, a link to further contact and other information, verification by those behind the study, and the insights and recommendations that arose from the process.

The “snapshot report” for the pilot generic PVC window profile ASF remains confidential within the industry. However, key insights emerging from its production include:

- Highlighting knowledge and data gaps, for example, about where additives are sourced;
- Recognition of the variability in sustainability performance between alternative additive substances, the supply chains they derive from, and the benefits of using recycled as opposed to virgin raw materials; and
- Insights into the sustainability benefits of including PVC recylcate, including this being a best option for containment of legacy additives used in a controlled loop as opposed to disposal and dependence on virgin resources. More details of how containment of lead stabilizer blended in appropriate recycled articles, progressively diluted over time as increasing proportions of lead-free PVC enters recycling streams, is discussed by reference [18] in terms of overcoming inherent conflicts between “clean chemistry” and cyclic economy goals.

Figure 5 presents a purely illustrative graphic representation of the overall scores per LCA stage/TNS System Condition assessment for Ca/Zn stabilizer, addressing each System Condition and life cycle stage. The “snapshot report” for the overall ASF of the EU generic PVC window profile includes similar graphics summarizing results for all six assessed additives. Running a sensitivity analysis of differing recyclate concentration, substituting for virgin Ca/Zn stabilizer, demonstrated that sustainability performance can be modified by alternative formulations, and the same observation is also true when data gaps are addressed.

DISCUSSION

ASF was developed to address linked environmental and social criteria, founded on robust, science-based TNS sustainability principles to address negative impacts and beneficial contributions from the use of additives throughout the full societal life cycle of PVC articles. The importance of accounting for sustainability across full product life cycles has been widely acknowledged (for example by the German Federal Environment Agency [9]). However, in describing progress toward “sustainable chemistry” goals, Blum et al. [8] revert to descriptions relating to reduction of negative impacts (“least adverse effects”, “chemicals without problematic properties”, “avoid unwanted outcomes or rebound effects”, etc.). Though important for sustainable development, this alone does not recognize the potential positive contributions of use of additives to sustainability as described in this article and by the German Federal Environment Agency [9].

ASF makes use of investments in preexisting assessments in addition to novel criteria collectively building a “full picture” of necessary conditions of sustainability. The societal life cycle takes account, for example, of alternative recycling or disposal options, transport of raw and intermediate materials, ethical and environmental issues associated with material sourcing, and positive contributions to the meeting of human needs as well as potential negative impacts. ASF assessment is built from sets of seven questions for each life cycle stage and TNS System Condition, spanning environmental, ethical, process management, and other forms of knowledge with allowance for knowledge and data gaps. Responses to questions remain accessible by those needing to scrutinize the assessment. If the same transparently recorded assumptions are made, assessments are replicable.

A common critique of assessment methods using qualitative criteria to address data gaps or integrate differing forms of evidence, a characteristic of ASF, is that they contain an element of subjectivity. McInnes and Everard [49] defend integration of qualitative with quantitative evaluations as essential for systemic sustainability assessment, as evaluations based only on criteria for which statistical data are available will be skewed toward only known concerns and priorities, disregarding wider implications and interconnections between different, systemically connected aspects including unforeseen problems and potential future risks. In fact, semiquantification is already widely deployed in industry and regulation, for
example in assigning risk criteria such as likelihood of timing, scale and reversibility of impacts.

An ASF for a finished article depends on suitable information being made available by suppliers of constituent additive suppliers, therefore constituting a nested approach as ASFs for each additive or other constituent supports overall sustainability assessment for finished PVC articles. Completed ASFs at each tier can serve as communication and learning tools, helping people in business and the regulatory community understand “bottlenecks” to sustainability across the whole life cycle of the article (for example ethical issues associated with material sourcing, excessive inputs to transport, maintenance requirements during life, inherent potential for and availability of infrastructure and markets for recycling, etc.). These bottlenecks are made visible as business risks or potential future liabilities, and therefore grounds for profitable innovation. Desk assessment of the use of alternative additives, novel additive substances, different additive production processes, or alternative suppliers or geopolitical regions, or if suppliers can address knowledge gaps including providing evidence of product stewardship, can all help improve overall ASF score by improving the contribution of article to meeting human needs or overcoming negative impacts. These requirements can be transparently communicated down supply chains for suppliers to take account of “hotspots” of sustainability concern, enabling more sustainable use of additives across finished PVC article life cycles. This potential for strategic guidance of innovations leading toward a vision of sustainable use of additives is illustrated in Fig. 6.

Currently, application of ASF has been completed for just one pilot article: the generic EU PVC window profile. Further testing is necessary at both the generic product category level (for example flooring, cables, etc.), and subsequently to differentiate specific products. It will often be necessary to protect some input information to maintain confidentiality of company-specific formulations, for example by password-protected access to data tables underpinning externally visible summary life cycle graphics. ASF thereby promotes a “coopetition” approach, a neologism describing collaboration at the generic levels of tools development and category assessment (for example via trade associations developing common tools and influencing regulators as in this pilot application) but enabling subsequent competition at the level of product differentiation on the basis of enhanced sustainability performance.

Development is ongoing to develop an online version of the ASF tool now the basic protocols are tested, with autofilling of generic information for some implementations of ASF, making assessment easier, quicker, and cheaper. The online tool can also serve as a vehicle for publishing outcomes while protecting commercially sensitive inputs.

Beyond the pilot development phase, ASF can serve many needs and users. For example, additive manufacturers may wish to conduct an ASF to assess, innovate and subsequently demonstrate to customers and regulators the sustainability benefits of the use of their specific additive substance. Trade associations covering generic additive types (e.g. stabilizers or plasticizers) may wish to raise awareness of strengths and also of problems requiring innovation, including supporting dialogue with regulators and policymakers particularly where positive contributions to meeting human needs have not been strongly communicated in the past. Trade associations addressing converted PVC applications (such as pipes, window profiles,

![FIG. 6. Illustrative usage of ASF findings to address areas of concern enabling progress toward the sustainable use of additives. [Color figure can be viewed at wileyonlinelibrary.com]](image-url)
or flooring) may also conduct ASFs to serve similar purposes. At individual company level, ASFs may serve valuable awareness, risk assessment, innovation, and communication purposes relating to the sustainability virtues and challenges of specific products.

However, the visibility of ASF to specifiers, retailers, and users of finished PVC articles is likely to be low. ASF makes contributions to the VinylPlus® goal of overall article assessment, development, and publication of relevant ASFs becoming a condition of the recently developed “VinylPlus® Product Label” [50] verifying that PVC products produced in Europe are fully and transparently compliant with measures to make progress with all five of the interconnected VinylPlus®/TNS sustainability challenges.

ASF also enables assessment of the specific contribution that use of additives makes to addressing other of the VinylPlus® sustainability challenges. This has particular implications, for example, for recycled content progressing Challenge 2 “Controlled loop management” (in the generic window profile example assessing different proportions of virgin Ca/Zn stabilizer versus Pb stabilizer in recycled PVC) and Challenge 5 “sustainability awareness” by providing information and supporting training relevant to the entire PVC value chain. Benefits of ASF assessment can also potentially extend beyond the PVC sector, for example by helping inform and demonstrate progress with wider societal goals including resource efficiency aspirations, emissions regulation for example under the EU REACH process, and the obligations of industry in addressing climate change [51]. ASF assessment can also contribute to issues identified both in the European Commission’s Toward a nontoxic environment strategy [52] as well as the Commission’s Circular Economy: Implementation of the Circular Economy Action Plan [53]. ASF can provide scientifically justified evidence supporting the longer-term resolution of inherent conflicts between these EC strategies, demonstrating that beneficial value recovery and reuse of legacy lead-containing end-of-life PVC in appropriate applications and with blending can constitute a “glide path” of progressive lead reduction as more lead-free PVC articles enter recycling streams (as described in [18]). Highlighting the benefits of value recovery and lower virgin inputs, ASF thereby supports various aspects positioning sustainability as a business opportunity for participants in the PVC value chain [54].

The systems-based approach embedded in ASF, founded on objective, comprehensive sustainability principles rather than currently known effects, also sheds light on the wider regulatory, resource use, recycling and other infrastructure, economics, and other societal dimensions necessary to enable fully sustainable use of additives. Suurs and Roelofs [55, p.2] recognized the need for system innovation leading to fundamental changes in both social dimensions, technical dimensions and, “very importantly, in the relations between them”. Realization of sustainable chemistry “…requires the transformation of value chains as well as institutional and financial structures…” [8, p.98].

Further factors yet to be addressed include where finished ASFs are to be published, their valid end-dates (or whether they are time-specific “snapshots”). Reappraisal of thresholds for additive assessment (the established REACH de minimus protocol was used in the pilot phase) may also be required or, alternatively, robust and transparent justification of how ASF is addressing the potential for substances to systematically accumulate in nature, deplete ecosystems, or undermine the meeting of human needs (i.e. compliance with all four interconnected TNS System Conditions). Further rigor is also required in determining confidence level in supporting data tables.

Pilot implementation on the generic EU window profile demonstrates that the ASF method is workable and robustly founded on science-based sustainability principles. It also shows that ASF makes use of preexisting investments, in addition to novel social and environmental criteria comprising a broader “picture” of necessary conditions of sustainability addressing multiple dimensions (ethical and environmental issues associated with material sourcing, transport, maintenance and alternative recycling or disposal options, and positive contributions to the meeting of human needs) associated with the sustainable use of additives throughout the full societal life cycle of PVC articles. A process for managing knowledge gaps is included. Inclusion of both “impact” and “progress” questions acknowledges that sustainable development is a journey from today’s unsustainable norms, also giving credit in a transparent and auditable way to commitments and future development programs and the positive contributions of the use of additives to overall article functionality and sustainability in meeting human needs. The ASF tool will benefit from further applications and refinement including digital automation to ease implementation. Overall, ASF demonstrates significant potential for moving assessment of additive substances from a potentially naïve basis in intrinsic chemical properties toward a systemic assessment of their use in the overall sustainability of PVC articles across full societal life cycles.

CONCLUSIONS

- ASF is a replicable, risk-based approach integrating the comprehensive, science-based sustainability principles (System Conditions) of TNS across the full societal life cycle of PVC articles to assess the sustainable use of PVC additives.
- ASF integrates different types of quantitative and qualitative knowledge (including environmental, ethical and process management dimensions), building on prior investments as “jigsaw pieces” contributing, with additional assessments, to assessment of a wider spectrum of socioecological dimensions of sustainability.
- ASF addresses issues at each life cycle stage though a generically similar set of three “impact questions” and four “progress questions”, accounting for knowledge or data gaps, as a stimulus for innovation by converters, resin manufacturers and additive suppliers to make transparent progress with sustainable development.
- Pilot implementation of ASF addressing additives within a generic European PVC window profile formulation demonstrates the operational applicability of the ASF process, also
highlighting significant knowledge gaps particularly relating to environmental as well as ethical issues in material supply chains.

- Sensitivity assessment based on comparison of two different impact modifier substances and their supply chains, as well as of recycled versus virgin PVC, demonstrates the value of ASF in differentiating the sustainability profiles of alternative formulations.
- Summary presentation of ASF outputs in graphic formats aids interpretation of “sustainability hotspots” and areas for innovation across the life cycle of PVC products.
- Further development of ASF, including online tools and autofilling of some question boxes, is ongoing as a contribution to the EU-wide VinylPlus® sustainability commitments.

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