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ROYAL SOCIETY OF CHEMISTRY

PAPER

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Cite this: DOI: 10.1039/d5su00930h

Life cycle based risk and opportunity mapping: a systematic collaborative procedure to integrate environmental and health aspects into early innovation for scoping and pre-screening for safe and sustainable by design (SSbD) assessments

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Received 19th December 2025
Accepted 1st April 2026

DOI: 10.1039/d5su00930h

rsc.li/rscsus

This article presents a method for life cycle based evaluation of early-stage innovations, addressing the lack of tools for assessing environmental aspects of emerging technologies. This approach supports the development of clean technologies, chemicals, and materials by fostering dialogue between inventors and evaluators through information exchange and preliminary assessments, even when data are uncertain. Aligned with the EU Chemicals Strategy for Sustainability under the European Green Deal, the Joint Research Center (JRC) introduced a framework for Safe and Sustainable by Design (SSbD) chemicals and materials, emphasizing application during early innovation stages when design choices can still be influenced. The proposed method, Life Cycle Based Risk and Opportunity Mapping (LCBROM), can be applied initially in an SSbD assessment to serve as scoping analysis and be revisited during the further stages of the SSbD process, promoting transparency and knowledge sharing among involved parties. Tested in four case studies focused on developing smart, safe materials and devices for clean air and water, LCBROM revealed that opportunity mapping is essential for engaging innovators but requires a benchmark technology or defined consequences of inaction; several screening methods exist for emerging technologies, yet none are widely adopted; and LCBROM meets four critical criteria for low-TRL tools: ease of use, inclusion of all relevant impacts, broad applicability, and low cost. The method enhances communication between developers, problem owners, and experts, improving mutual understanding, and continues to be refined and validated in ongoing research programs.

Sustainability spotlight

Emerging technologies often lack effective tools for early-stage environmental and health assessments, risking unsustainable design choices. Addressing this gap is crucial, as early decisions can lock in negative impacts. The Life Cycle-Based Risk and Opportunity Mapping (LCBROM) method enables transparent, collaborative evaluation of innovations at low technology readiness levels, systematically identifying both risks and opportunities across all life cycle stages. By fostering dialogue among stakeholders and highlighting critical hotspots, LCBROM guides safer, more sustainable innovation trajectories. Its ease of use, broad applicability, and low resource demand make it a valuable pre-assessment tool, supporting the EU's Safe and Sustainable by Design (SSbD) framework and advancing responsible environmental decision-making in technology development.

Introduction

In early innovation, there are typically challenges in addressing all design principles and considering various stakeholders with different interests. A well-known problem in technology assessment is linked to what is known as the "Collingridge dilemma" – many impacts of new technologies on society are initially not fully understood and also not fully determined. Decisions that are taken during an innovation process are based on current knowledge and assumptions and lead to commitments and investments, which also means that once a trajectory is chosen, many options can no longer be pursued, due to, among others, a lack of remaining funding. A review of Collingridge's approach and subsequent research on responsible innovation points out that a main contribution remains a more transparent and explicit analysis of conditions during an innovation process. Qualities needed to address these challenges are, among others, inclusion, openness, incrementalism, flexibility and reversibility.[1] Collingridge addresses large scale developments that involve many

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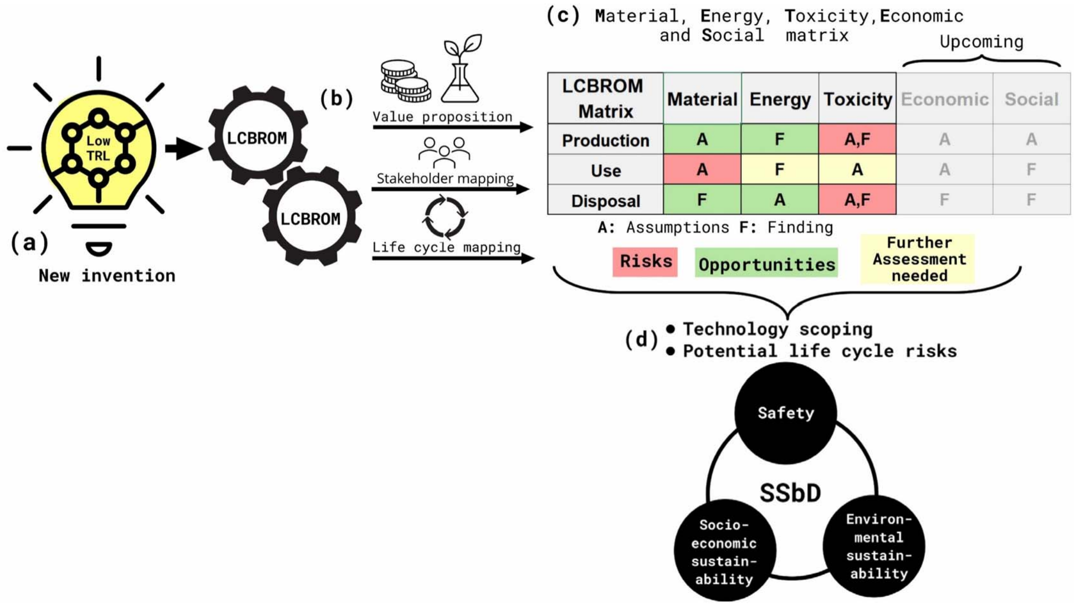

Fig. 1 The LCBROM methodology to assess (a) early innovations in chemicals, materials, or processes. The (b) collaborative LCBROM assessment includes a value proposition for the innovation, a mapping of relevant stakeholders for further assessment, and a life cycle mapping of the process or product system. Risks and opportunities at all life cycle stages are systematically analyzed and summarized in a (c) Material, Energy, and Toxicity (MET) matrix. This methodology serves as a (d) pre-assessment for SSbD, supporting technology scoping and identifying potential hotspots for life cycle risks in early innovations.

different stakeholder groups including society in general. Based on similar prerequisites with a focus on involved parties, the (eco-) design paradox acknowledges a lack of information during early stages and a lack of options to change and improve design, mostly related to costs.[2] As a response to the need to collect information and knowledge about data gaps in early innovation, we suggest the use of Life Cycle based Risk and Opportunity Mapping (LCBROM), conceptually illustrated in Fig. 1.

LCBROM is a predominantly qualitative screening approach to investigate potential risks as "red flags" and "critical hot spots" based on available information in early innovation by considering all life cycle stages (material sourcing, production, use, and disposal). When a benchmark/reference technology with known risks and shortcomings is established and is to be replaced, the advantages of the innovation can be highlighted as opportunities by comparison. The goal of LCBROM is to analyze concerns and opportunities for innovations at low technology readiness levels (TRLs)[2] to guide the development toward a more safe and sustainable solution. Where quantitative results from other studies are available in a suitable format (*e.g.*, from previous transparent and reviewed life cycle assessments of related materials or processes), they should be considered. For some substances, complementary hazard and risk assessments may be performed to better understand results related to toxicity impacts. Transferable results from completed LCBROM studies may be stored as modules in a repository for easy access on later occasions. This also requires storing documentation of assumptions and background data to evaluate and adjust them where necessary.

In 2020, the European Commission (EC) presented the Chemicals Strategy for Sustainability as part of the European Green Deal.[3] The strategy calls for a transition toward the use of safe and sustainable chemicals, materials and processes. To address these development goals, the Joint Research Centre (JRC) has published the Safe and Sustainable by Design (SSbD) framework for chemicals and materials, along with a definition and criteria for the evaluation procedures.[4] A revised version of the framework published in 2025 considers feedback from initial case studies and road-testing and suggests a scoping analysis as the initial stage.[5]

A main pillar of the SSbD framework concerns the (re)design of chemicals and materials. It is intended to guide inventors toward safer and more sustainable designs at an early development stage, when parameters are not yet fixed and there is still a high degree of freedom for changes and optimization. Both radical and incremental changes can be addressed. The framework presents a (non-exhaustive) list of design principles to consider during the (re)design. The initial scoping analysis includes a system description and a description of the intended innovation based on a set of SSbD principles (SSbD1 to SSbD9) that are derived from different contexts such as green chemistry, green engineering, energy efficiency, sustainability chemistry criteria, golden rules and circularity chemistry principles. The principles address aspects of resource use and emissions in a life cycle perspective and refer to environmental aspects as well as social risks. The main part of the SSbD framework covers safety and sustainability assessment of the chemical/material.[5] To facilitate the SSbD scoping, LCBROM can serve as a starting point for exploring the entire life cycle of the innovation (the innovation being a chemical, process, material, or product). Throughout this process, the innovation is assessed qualitatively and, where possible, quantitatively against environmental impact categories that emphasize human- and environment-related risks and opportunities in different life cycle steps. Opportunities, in this context, are reduced impacts and can also be related to better performance of the innovation, or fewer side effects, including waste streams and emissions. During LCBROM, the technology developer gains indicative insight into how their innovation, with its intended implementation, potentially affects humans and the environment across different life cycle phases by identifying key hotspots. For this to be effective, the safety and sustainability expert leading the assessment must develop an understanding of the function of the innovation and how it is integrated into a product system or process application, as well as its production, use, and disposal scenarios. The purpose of the LCBROM is not to replace any quantitative assessment, but rather to pinpoint potential hotspots for upcoming assessments and to identify knowledge and information gaps. Consequently, parts of the life cycle for which available information is sufficient to indicate low or negligible negative impacts on human and/or environmental health and safety can be accepted as is without further consideration in the first assessment stage.

Several other tools have been proposed for assessing environmental aspects of innovations at low TRLs in the past. An early example is the 5 × 5 matrix reported by Graedel *et al.* called the Environmentally Responsible Product Assessment Matrix (ERPA).[6] In that matrix, an innovation is assessed with regard to material choice, energy use, solid residues, liquid residues, and gaseous residues using a life cycle perspective. The assessment is qualitative in nature, in which expert input, surveys and checklists are used to derive a figure of merit for the innovation. Another tool that may be used for assessments in early innovation is the concept of the Material Input Per Service (MIPS) unit developed at the Wuppertal Institute.[7] MIPS considers predominantly resource use and assumes that this correlates with potential emissions. Detailed evaluation of different types of contaminants and the severity of their effects is beyond the scope of this work. Other examples are the Life-Cycle e-Valuation by Lang-Koetz *et al.*, the methodology for integrating sustainability considerations into process design by Azapagic *et al.* and the Environmental Effect Analysis (EEA) by Lindahl & Tingström.[8–10] General strategies have been outlined as an extension of life cycle assessment (LCA), hybrid analysis and toolbox approaches.[11] The method presented herein, LCBROM, has been inspired by the already existing tools, but essential elements have been added and adjusted to ensure that the method (i) is easy-to-use, (ii) includes all relevant impacts, (iii) has a wide domain of applicability, and (iv) has a low resource demand in terms of time and money.

Long before the EC launched the SSbD framework, Lang-Koetz *et al.* (among others) recognized the need for environmental assessments of product ideas and concepts in early innovation and how this could be done by applying life cycle thinking and integrating environmental assessment into the innovation process.[8] In our work, we have built upon the research questions explored by Lang-Koetz *et al.* while also incorporating opportunity mapping, which we recognize as a powerful driver for decision-makers. Moreover, the discussion of opportunities in terms of the value proposition of the innovation can strengthen the engagement of technology developers. This approach fosters greater involvement in the assessment, which may be lower if the focus is solely on risks and environmental concerns. Hence, our research explored the question: *How can risks and opportunities of innovations be assessed at low TRLs?*

In this article, we introduce a method to be used for life cycle based appraisal in early innovation to fill the gap in tools for evaluating emerging technologies. To evaluate the method, it has been applied in four case studies in the research programme Mistra TerraClean: (i) development of a technology to concentrate rare earth elements (REEs) from water at a discontinued mine; (ii) application of iron sulphide doped activated carbon to remove mercury from a side stream in an enrichment plant; (iii) chemical modification of PEX material to prevent unwanted bacterial growth in drinking distribution water systems; (iv) removal of CO_2 from indoor air with filters based on cellulose nanofibrils and activated carbon. All the technologies in the case studies were at low TRLs when the technology concept and application were formulated. The first of the described case studies will be used as an example in this article. All applications in the case studies are related to material and device development to treat emissions to water and air from current processes smartly and to treat contaminated areas while recovering resources.

Methodology

The structured development of LCBROM

This article highlights the absence of tools that can assess human and environmental impacts of emerging technologies in an easy, comprehensive, and cost-efficient way. We address this issue by presenting a method that can serve as a tool for fulfilling these requirements. While doing so, we also present the structural procedure for our method development, inspired by the development of the Circular Strategies Scanner, which was developed using the Design Research Methodology (DRM).[12,13]

We initiated the method development during the fall of 2022. To describe its development journey, we have chosen to divide it into three phases, all containing a descriptive study and a prescriptive study. Fig. 2 describes the aim and main outcome of each phase, while Table S1 in the SI describes more details on each phase, including the main activities.

The procedure for carrying out an LCBROM

The LCBROM method is based on an iterative process, illustrated in Fig. 3, with continuous interaction between involved parties and identification of stakeholders to derive potential risks and opportunities of the innovation. Risks and opportunities at all life cycle stages are systematically analyzed and summarized in a Material, Energy, and Toxicity (MET) matrix†.

† van Berkel *et al.* cite a report by Brezet and van Hemel from 1994 as the origin of the MET matrix, which is now out of print. Note that the accessible version by van Berkel uses the term "toxic emissions"; this is broadened in the LCBROM matrix to also include aspects of toxicity related to products and by-products.[30]

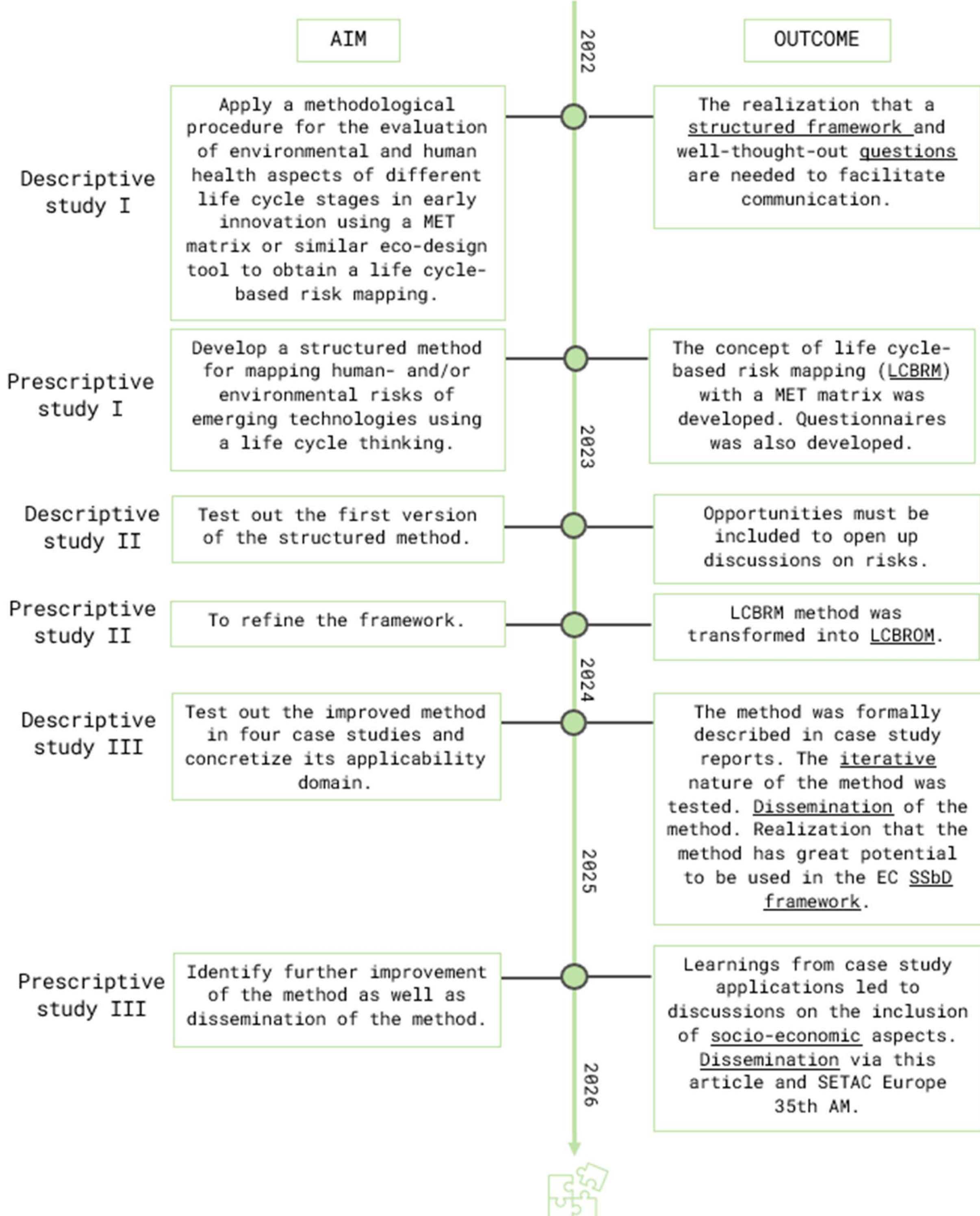

Fig. 2 The structured development of LCBROM divided into three phases, all of which contained a descriptive study and a prescriptive study.

It is recommended to have the MET matrix in mind throughout the whole assessment. To guide the LCBROM practitioner, a non-exhaustive list of questions to keep in mind during the assessment is presented in Table S2 in the SI.

Initiation and framing of LCBROM assessment

An LCBROM is ideally initiated once there is a distinct application for the innovation and laboratory experiments show positive results. The first step for the LCBROM practitioner

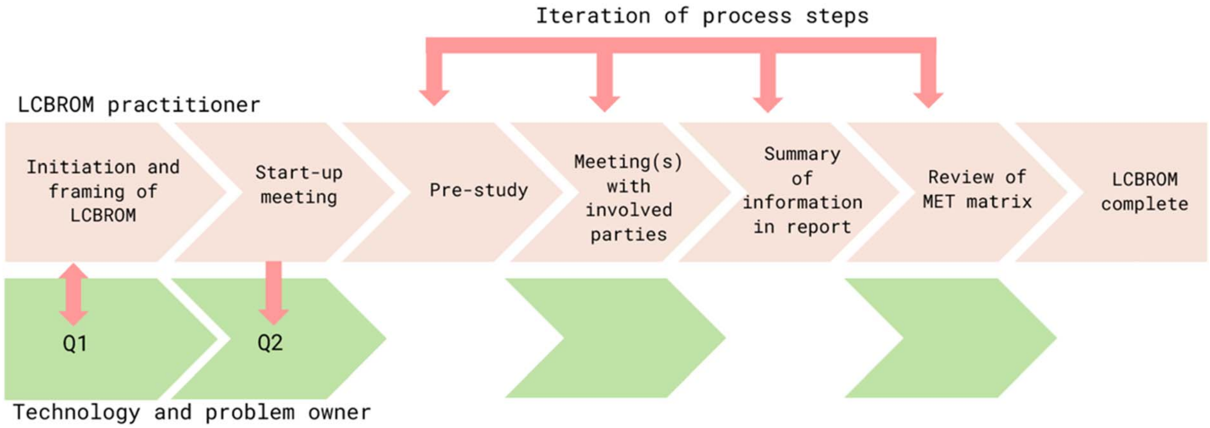

Fig. 3 Flowchart describing the steps of the LCBROM method. The arrows represent the iterative nature of the process. Q1 and Q2 indicate questionnaires that may be used in the initiation and framing of LCBROM as well as during the start-up meeting for early information gathering, both available in Table S3 in the SI.

(often someone with an LCA background, not necessarily involved in material development) is to perform an initial mapping of involved parties and stakeholders. As there are several actors involved with different expertise and goals, this mapping is an essential part of the LCBROM method to ensure that the LCBROM practitioner can access the right information and data needed to perform a useful assessment. The core team in the LCBROM assessment could be rather small in the beginning, for example, a three-person team with competencies in LCA, risk assessment, and technology systems, and successively expanded during the course of the assessment. The mapping facilitates this expansion of the LCBROM team. Not all actors need to be actively involved in the assessment. As an example, representatives of a competing solution might be excluded at this stage. It is, however, recommended to identify independent experts who can support the development by defining the state of the art.

Note that the mapping done here does not imply that the affected stakeholders, as defined in social life cycle assessment, are already covered. For a social assessment, it is required to identify who is affected by the innovation once it is fully implemented, and typically that includes workers, local communities, society, value chain actors, consumers and children. Identifying which stakeholder groups might be affected and in which subcategories changes can be expected is an additional task to familiarize technology developers with concepts of social assessment. Involving representatives at an early stage is challenging, as the location and supply chain have not been decided. Options to further develop the MET matrix and include economic and social aspects are cursorily discussed in the outlook, but have not been fully explored in the case studies presented herein. This is equally the case for any type of cost or economic assessment. Identifying necessary investments as a basis for capital expenditure and resources to operate an innovative process is recommended. Costs for a scaled-up and integrated industrial process are expected to decrease compared to low TRLs. The revised SSbD framework addresses socio-economic sustainability assessment and distinguishes between aspects that are independent of technology features and can be evaluated at an early stage with low TRLs and those that need a clear understanding of the actual implementation.[5] This will be considered in an expanded version of the MET matrix to a METES matrix, also accounting for economic (E) and social (S) aspects. This expansion was not tested in case studies.

Once the mapping is completed, an information meeting is recommended at which the LCBROM method can be presented. During such a meeting, we suggest that the strengths and limitations of LCBROM are discussed to ensure reasonable expectations of the upcoming assessment, both in terms of actual results and what will be required from involved parties.

After the information meeting, a questionnaire (Q1) may be sent to the identified participants. The purpose of Q1 is to document the problem definition, including a background describing a specific case, benchmark technologies (if any) with known risks and shortcomings, and participants as well as stakeholders involved in the case. Note that the purpose of the questionnaire is to support the LCBROM practitioner in determining what information is needed at the start of the LCBROM assessment. Depending on the dynamics of a working group (*e.g.*, technology owner, problem owner, and LCBROM practitioner), an approach without questionnaires may be applied to populate the MET matrix, for example, using documentation from dialogues or workshops.

Start-up meeting

The purpose of the start-up meeting is to initiate the LCBROM assessment. The following topics may be discussed.

- Introduction of the LCBROM purpose and method.
- Problem definition.
- Introduction of the technology/material and the intended application.
- Discussion on benchmark technologies.
- Discuss any uncertainties regarding Q1 (if relevant).
- Discuss how to handle confidentiality, *e.g.*, patent applications and the need for a non-disclosure agreement.

The purpose of the meeting(s) with involved parties in the assessment is to populate the MET matrix. Moreover, the meetings provide an opportunity to initiate a dialogue among involved parties about technological developments and the associated life cycle based risks and opportunities. The workshop allows participants to learn from one another and to establish a common ground and a trusting atmosphere where ideas and information can be freely shared. To simplify that process, a second questionnaire (Q2) may be sent after the start-up meeting to allow the technology owner and problem owner to reflect upon the technology from a material, energy, and toxicity perspective. For that reason, the questions in Q2 may be briefly discussed at the end of the start-up meeting. The questions in Q2 lay the foundation for the agenda of the upcoming meeting(s); hence, no answers to Q2 are expected beforehand.

Pre-study

At this step, the LCBROM practitioner is supposed to initiate a literature review, scanning the availability of existing studies of the benchmark technology. Such studies could, for example, be LCAs and/or risk assessments. The answers added to Q1 may serve as keywords for this literature review. Depending on whether (life cycle impact assessment) methods are up to date and described transparently, this can either be used immediately or replicated to fill in data in the matrix.

The pre-study also includes documentation of the problem definition in the report template. Potential usage(s) of the innovation should be described to facilitate a life cycle perspective of the appraisal. If there are no specific use cases for which the innovation is being developed, it is recommended to define an assumed case to consider the full life cycle and identify opportunities. Benchmarks should be at least state-of-the-art, meaning that the technology to which the innovation is being compared should be the most advanced and sophisticated alternative currently available.

Meeting(s) with involved parties

As the LCBROM procedure is iterative, several meetings are likely needed during the process. The involved parties and LCBROM practitioner(s) should discuss the questions in Q2 and fill in a MET matrix. When answering the questions, both risks and opportunities should be considered. If any risk mitigation measures are planned, this should also be described. Knowledge gaps identified during the discussion should end up as action points for further work by either the LCBROM practitioner, material developer, or problem owner to reduce uncertainties of the appraisal.

Summary of information in a report

The draft report for the LCBROM is continuously updated throughout the entire process. Toward the end of the appraisal, the LCBROM practitioner is supposed to refine the information already added to the template and wrap up the mapping using the MET matrix, introduced in Fig. 4, and finalize conclusions and recommendations.

Every cell in the MET matrix combines either material, energy, or toxicity related to the life cycle stage, such as material use in production or energy use during disposal. Input added to the matrix should be self-explanatory in the sense that the reader should understand the underlying message without consulting the bulk text.

Depending on whether different aspects are identified as opportunities, risks, or areas requiring further investigation,

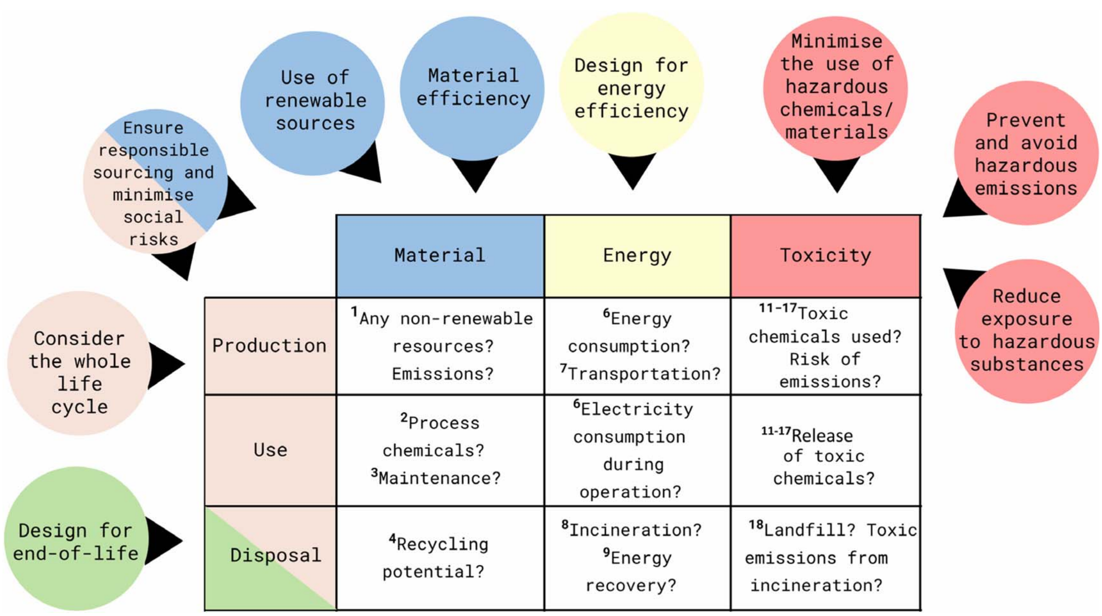

Fig. 4 SSbD design principles (colored bubbles) connection to the MET matrix used in LCBROM. The questions provide examples of discussion points for an LCBROM and the numbers refer to specific questions in the more comprehensive (although non-exhaustive) list of questions in Table S2 in the SI.

a color coding is suggested (*e.g.*, a traffic light system assigning green to opportunities, red to risks and yellow to findings that require further research) to provide a better overview. Data gaps should be denoted DG and be left uncolored. Although most information in the MET matrix comes with uncertainties due to low TRLs, some may be particularly uncertain, and highlighting those with an italic font is recommended. LCBROM practitioners may also have different opinions about certain aspects due to a lack of information, which can be solved by applying the yellow category in the traffic light system indicating that further research on the topic is needed.

The results from an LCBROM can be used for several purposes, depending on the scope of the mapping and a future assessment. If the objective of the appraisal is to guide the innovation towards a more sustainable alternative compared to a benchmark technology, the results may be used for decision-making, including a decision about potential next steps, such as a more complete assessment. In general, it is not just the MET matrix itself that represents the main result. Equally important are the lessons learned during the appraisal regarding life cycle mapping and system understanding, which may lead to an optimization of the new invention ((re)design) if negative impacts are identified. The method also helps envision potential value chains for the new technology.

How does the LCBROM method support SSbD assessment for technologies in early innovation?

LCBROM is a tool for early review of the life cycle stages and potential risks and opportunities of an innovation for which there is an insufficient amount of data available for performing more sophisticated assessments, such as LCAs. The integration of human and environmental health evaluations in early innovation of chemicals/materials has been rising on the agenda for the last couple of years, not least because of the publication of the SSbD framework and its methodological guidance.[5,14] Even though LCBROM was not originally developed for the sole purpose of SSbD assessments, its usefulness is expected to be high. Hence, this section exemplifies how the method can support SSbD assessments.

The (re)design phase

Improvements made during the design phase potentially have a larger impact on the environmental performance than improvements implemented at a higher TRL when many decisions are already established.[15] LCBROM allows the innovation to be successively improved using a systematic MET matrix as a tool to evaluate the completeness and balance of information. Applying the SSbD design principles to the MET matrix facilitates the evaluation of the (re)designed material against Material, Energy, and Toxicity using a life cycle perspective at an early stage. The connection between the MET matrix and the eight (non-exhaustive) SSbD design principles is illustrated in Fig. 4. Note that the revised framework contains a ninth principle Ensure responsible sourcing and minimize social risk, which is foremost applicable for socio-economic aspects and were not included in the tool testing.[5]

Scoping

Scoping in SSbD is the initial analysis phase that establishes the assessment's purpose, system boundaries, and the chemical or material to be examined. It lays the groundwork for all subsequent safety and sustainability evaluations. During this phase, the system and its life cycle stages are defined.[14] The LCBROM procedure can serve as a structured approach for this scoping exercise, helping to develop a clear problem definition, map the life cycle stages, identify relevant involved parties and potential external stakeholders, and discuss (re)design options at an early design stage.

The safety and sustainability assessment

Safety assessment. The starting point for an SSbD assessment according to the SSbD framework is to investigate the intrinsic physico-chemical properties of the chemical/material being developed. This is intended as a common entry point for the safety assessment and environmental sustainability assessment and is followed by an initial assessment of intrinsic hazards.[5] Even though the LCBROM method does not serve as a tool itself to assess the intrinsic hazard of the chemical/material, it requires that the technology developer start thinking of the innovation in terms of toxicity early on and add information to the MET matrix. Depending on the competencies in the working group and resources available, exploratory toxicity assessments can be performed to add to the MET matrix. This has been tested in a couple of case studies, one of which is introduced for illustration in this paper.

The life cycle perspective, more specifically, cradle-to-gate (gate being the production and processing phase), is introduced early in the SSbD framework and is also proposed for risk and exposure assessment. Performing an LCBROM before the SSbD assessment would result in a smoother transition toward expanding the scope, since the life cycle and the supply chain are identified. Occupational hazards in a preliminary supply chain can thus be identified. As the purpose of LCBROM is not to deliver a quantitative assessment, it is not intended to replace any occupational risk assessments. However, it may pinpoint hotspots to separate those areas of the life cycle that may require further attention. Requirements for protective equipment and prevention through layout (encasing processes and logistics) can be identified and discussed with the technology developer.

The following step of the SSbD framework focuses on human health and environmental aspects in the (final) application phase of the innovation. Mapping potential risks and opportunities of the use phase is included in the LCBROM method and could potentially serve as a starting point for the quantitative assessments in this step.

The innovations considered in the four case studies (introduced earlier in this article) were mostly applied by professional users. From a toxicity perspective, it is important to establish whether the innovation is intended for consumers and/or professionals. Consumers are likely not trained to use personal protective equipment (PPE) while professionals are, meaning that the risk of exposure may be higher for consumers than for professionals. Innovations that are used indoors may also contribute more to exposure.

Assessing the innovation regarding energy consumption during different life cycle stages is an important part of the LCBROM. In the use phase, energy consumption can be related to climate change and pollution if fossil energy carriers are used.

Environmental sustainability assessment. The core of the environmental sustainability assessment is life cycle assessment (LCA) following the procedure suggested for product environmental footprints, which poses a challenge for materials in early innovation (*i.e.*, those at low TRLs). Challenges associated with LCA in early innovation were pointed out by Hetherington *et al.*[16] For example, the challenge of future unknown features and data gaps was discussed. There may be data gaps considering different life cycle stages, upscaling parameters, and emissions. In addition to those challenges pointed out by Hetherington *et al.*, it is very costly to perform a full LCA, both in terms of effort and money. Hence, there is a need for life cycle based tools for assessing innovations at low TRLs when many options with minor differences between them are available, which was also pointed out by Moniruzzaman Moni *et al.*[15] A common approach is to model process systems based on a benchmark process and adjust parts based on the specification. However, published data for benchmark processes may be aggregated and thus representative for average industry processes, but not suitable to guide the development of innovations and identify relevant parameters.

Challenges of performing an LCA at low TRLs (<5) were specifically pointed out in the first version of the SSbD framework.[4] To overcome such challenges, the framework suggests the use of Prospective LCA. The revised framework introduces the term Maturity of the innovation which may include different approaches (such as TRLs) to define the maturity level of the innovation. To assess innovations at low innovation maturity, the revised framework emphasizes a broader scope of assessments focusing on the use of screening level assessments and LCA based benchmarks instead of specifically suggesting prospective LCA.[5] Nevertheless, the interest for such LCAs is increasing and the challenges associated with it may be solved using specifically designed frameworks. Examples of such frameworks are proposed by Piccinno *et al.*, Buyle *et al.*, Arvidsson *et al.*, and Thonemann *et al.*[17–20] However, we would argue that the use of prospective LCA would benefit from the application of an LCBROM in advance. For example, applying LCBROM at TRLs 1–2 low the LCA practitioner to map the life cycle and understand what type of challenge they may face during the upcoming assessment once the technology reaches TRLs 3–5. Additionally, the SSbD framework calls for the application of LCA for all uses and production routes of the innovation. Performing a (prospective) LCA for all those scenarios will be costly and time-consuming. Having applied LCBROM in advance would enable the LCA practitioners to gain an understanding of the most likely areas of concern and, hence, require extra effort in estimating their input parameters.

Applying the SSbD concept in early innovations requires tools and methods that are adapted to low data availability and high uncertainty. Except for prospective LCA, there are no such methods communicated in the SSbD framework or its guidance for the life cycle based assessment. Some tools exist (or are under development), for example, the screening level approach developed by Pizzol *et al.* that specifically addresses multicomponent nanomaterials.[21] It uses extensive questionnaires that may be difficult for technology developers to answer; hence, expert input may be required. Another example of an existing tool is the ERPA matrix.[6] Although there are existing tools, none seem to capture all the necessary ingredients for being *the commonly applied* tool for emerging technologies: (i) easy-to-use, (ii) inclusion of all relevant impacts, (iii) a wide domain of applicability, and (iv) low cost in terms of time and money. We would argue that LCBROM could potentially fill that gap in tools because of its iterative nature and use of general questions that can be applied to most technology fields.

As already pointed out, there are not enough data to perform full LCAs at low TRLs. Instead, LCBROM can be used to map out relevant life cycle stages and identify potential risks that the material use entails during upscaling. Additionally, if there is a benchmark technology available on the market, LCBROM can also identify potential opportunities for the innovation, based on known shortcomings of the benchmark technology. Identifying such risks and opportunities will help to reduce lock-in to unsustainable decisions and to continuously improve the material. As the material reaches a higher TRL and more data become available, the LCBROM can be further refined. Eventually, there will be enough information on the innovation to perform a screening LCA and finally a full LCA, if necessary. Hence, LCBROM could serve as a starting tool for the life cycle based assessment of the SSbD framework for materials in early innovation.

Socio-economic sustainability assessment. The socio-economic sustainability assessment was added in the revised SSbD framework and not available during our study.[5] It is based on societal life cycle costing (LCC) and social life cycle assessment (S-LCA) and proposes a limited selection of indicators to evaluate social fairness, competitiveness, and societal life cycle costs. This step was voluntary according to the 2022 version of the SSbD framework. But we have initiated discussions on how to incorporate social and economic factors into the LCBROM approach. Starting a dialogue with problem owners and technology owners provides options to identify involved parties and stakeholders and explore viewpoints. This was not explicitly included in any of the case studies and is therefore out of the scope of this article.

Case study results

LCBROM has been applied in four case studies, one of which was exploring whether mining wastewater can be turned into a source of REE. There are currently few regions that can produce REEs, which may become an issue when the global demand continues to increase, as a consequence of, for example, the increased use of electric-vehicle motors.[22] To overcome this issue, the case study group explored an alternative REE recovery method by concentrating REEs from a discontinued mine using a hollow fiber supported liquid membrane (HFSLM).

A rough life cycle description of HFSLM is described in Fig. 5, which consists of material production *via* impregnation, use *via* selective sorption of REE, and disposal *via* incineration and/or recycling. Within the use phase, there is a selective sorption of REEs to optimize the REE recovery. The main purpose of this step was to remove elements that may compete with REEs in terms of sorption sites and extractants. Thereafter, the low-concentration water is concentrated by allowing the water to pass through the liquid membrane to form metal complexes with organic extractants. These complexes are thereafter diffused *via* a membrane where metal ions are delivered into a stripping solution. The high concentration solution can now enter the separation stage, from which separate REEs are obtained.[22]

An LCBROM was performed in parallel to early lab tests to support and guide the decisions towards safer and more sustainable solutions. After the initial steps of the LCBROM were performed (initiation & framing of the appraisal and start-up meeting), a pre-study was conducted. During that study, solvent extraction was identified as the main benchmark technology to be used for opportunity identification.[23] For that purpose, a literature review was performed to identify the major challenges that solvent extraction faces from an environmental point of view.

The first significant finding, also identified by Navarro & Zhao, was that there are very few LCAs (or other articles focusing on the environmental impacts) of REE production, and specifically for the solvent extraction step.[24] In fact, we only found two articles focusing on the solvent extraction phase.[25,26]

This was somewhat surprising, as the second finding was that the main contributor to the overall environmental impact in REE production seems to be the solvent extraction step (approximately 30% according to Vahidi & Zhao).[26] It should, however, be noted that most articles highlight that there are, in general, very few LCAs on REE production in combination with poor data quality and information.[27]

The use of hydrochloric acid (HCl) in solvent extraction was identified as a challenge since it is being used in high quantities, which generates a significant environmental impact.[25,26] For that reason, using lower amounts of HCl, or no such use at all, was highlighted as an opportunity for the novel technology. On the other hand, both alternatives, solvent extraction (benchmark) and HFSLM (innovation), use kerosene, which is a petroleum-extracted mixture of aliphatic and aromatic hydrocarbons, cycloalkanes and alkylbenzenes with varying structures and toxicities. As such, there is high uncertainty in establishing safety risks with this mixture since various compounds in the mixture are more toxic than others. Many of the potential components of kerosene are known to be mutagenic and reproductive toxic as well as highly toxic to various organs. Due to its toxicity, the use of kerosene was marked as a risk in the MET matrix. Table 1 provides a simplified MET matrix from the case study, anonymized to avoid disclosure of confidential information.

Once the first draft of the MET matrix was delivered to the technology owner, it was presented to the steering group of the research programme, enabling an early-stage peer evaluation. Based on feedback from that presentation and the content of the MET matrix, the iterative nature of LCBROM was tested. The findings of the LCBROM were refined, and the technology owners decided to investigate the possibility of substituting kerosene. This was first done *via* a toxicity assessment, in which the hazards of kerosene were mapped. Secondly, a literature review was performed, in which it was found that alternatives for kerosene are available.

Due to the end of the Mista Terra Clean research programme, this study could not follow the further development of the innovations towards a higher TRL, which would have allowed for a more refined LCBROM. Despite this, the LCBROM demonstrated its potential in identifying risks and opportunities to guide the innovation towards a more sustainable alternative.

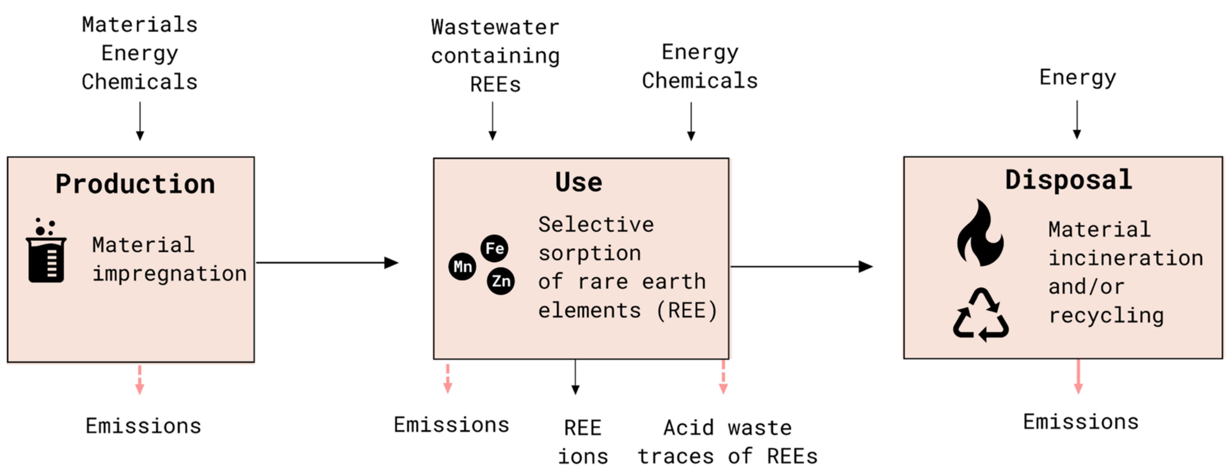

Fig. 5 Life cycle description of the technology used for retrieving REE from wastewater from discontinued mines.

Table 1 Overview of a MET matrix from a case study conducted in Mistra TerraClean. Color code: green = opportunities, red = risks, and yellow = further research is needed. Findings and assumptions are denoted F and A, respectively. Note that some entries from the case study are excluded for simplicity

	Materials	Energy	Toxicity
Production	F: Possibly use of recycled and/or renewable polypropylene and polyethylene in the HFSLM.	F: Information from membrane suppliers indicates that the production process is not energy intensive.	A: Production of solvents and extractants may release toxic emissions.
Use	F: Upscaling is difficult because of gel formation which occurs at sub-optimal operating conditions.	F: Possibly less energy intense than the current? state-of-the-art technology.	F: Less hazardous extractants needed. F: Use of kerosene.
Disposal	F: Hazardous waste containing acids must be handled.	F: The HFSLM is likely to be incinerated.	A: Waste may contain traces of metals.

The appraisal also contributed to a learning process within the LCBROM team regarding the method and it introduced a systematic life cycle perspective to the project partners, especially the technology developers, who had not previously considered potential life cycle impacts in their work processes. The LCBROM was therefore effective as a guiding tool and was appreciated by the participants, particularly the technology owners.

For future work, it would be interesting to compare the results with those of a more rigorous, quantitative assessment once the innovations reach a higher TRL, in order to evaluate the precision of the predictions presented in the LCBROM.

Discussion

Using a matrix to summarize learnings from a life cycle based assessment has been done since 1995, when the ERPA matrix was introduced.[6] The appraisal is qualitative in nature, in which expert input, surveys and checklists are used to derive a figure of merit for the innovation. LCBROM is a modernized version of this tool with some commonalities and differences. An important difference is that the ERPA matrix is used as a grading system for deriving a single score to be used for tracking improvements.[6] As LCBROM is intended to be used for hotspot identification for a variety of technology types, a scoring system has not been deemed necessary at this point.

Another key difference between LCBROM and the ERPA matrix is the ability to identify opportunities. To ensure that innovation results in a lower human and environmental impact than the current technology, opportunity mapping is just as important as risk mapping. Since LCBROM is designed for early-stage innovation, the developer has the chance to refine the innovation regarding its production process, usage, and/or future waste treatment in terms of material, energy, and/or chemical choices. Therefore, LCBROM requires a reference technology to identify opportunities. If no reference can be established, the comparison should be made against a scenario where no action is taken at all.

As established in the Introduction, several other tools have been suggested throughout the years in addition to the ERPA matrix. We see several similarities between these approaches and LCBROM, for example, the qualitative life cycle based questions that identify pathways for more sustainable innovation. Additionally, the EEA framework explicitly states that the assessment is designed to be carried out in a multifunctional team,[10] which aligns with LCBROM in the sense that a small team of experts is recommended to be involved. Specifically, a three-person team is recommended in which competencies of LCA, risk assessment, and technology systems are required.

A main characteristic that distinguishes LCBROM from other qualitative and/or semi-qualitative life cycle based appraisal tools is the O in LCBROM, *i.e.*, the mapping of opportunities. We have found that the inclusion of opportunities in the assessments opens up the willingness of different involved parties to put resources into performing human health and environmental appraisals in early innovation. Problem owners understand that this dialogue can help to identify advantages of alternative solutions beyond sufficient performance and select among different options. The inclusion of opportunity mapping allows the technology owners to tailor their offerings to avoid shortcomings of current solutions while also reducing elements of "optimism bias". For the technology owner, the O may also be used to pitch the advantages of the innovation to potential investors, and considering life cycle risks might make it even more attractive. Additionally, it allows for the identification of multiple uses of the innovation and/or prolonged life cycle of the material within the technology. Another characteristic that distinguishes LCBROM from other approaches is that its result is presented in an easy-to-understand format using a MET matrix. That facilitates a quick and transparent result communication to decision-makers and other experts, which also allows for further improvements *via* iterations through quick feedback routes. The latter has been tested in a couple of case studies with a positive response.

During the development of the method and its application in case studies, it became clear that the formalized stepwise approach and defined input information facilitated the execution of the method. The MET matrix is intuitive and easy to understand, which is important as there is a strong need for tools that can be used by small and medium-sized enterprises (SMEs). Although SMEs may not have the resources and/or competence to carry out an LCBROM themselves, SMEs possess technological expertise that is essential in the execution of an LCBROM.

A well-thought-out and defined working group is crucial to obtaining a successful LCBROM, as there must be a common understanding and driving force for performing the appraisal, as well as the possibility of getting access to the right information. A common understanding of the strengths and limitations of LCBROM is important to establish early on. Additionally, to derive a successful LCBROM, non-disclosure agreements may have to be signed. If no such agreement is signed, it can be difficult to identify risks and opportunities if there is resistance in sharing sensitive information. However, if non-disclosure agreements are signed, it may be difficult to publish the results from the assessment, which ultimately may hinder further development of the method itself. To solve such an issue, the LCBROM practitioners are recommended to carry out the assessment as far as possible using the shared information and present the result to the technology and problem owner. While doing so, it is important that the result is communicated in a way that clearly points at the relationship between uncertainty and data gaps. It should also be explained that more reliable results will come with more transparent information sharing.

Future outlook

Although the concept of the MET matrix is well established for eco-design projects, its use for the purpose of assessing innovations at low TRLs is under development. For that reason, the LCBROM method has several areas for improvement, and some will be addressed in upcoming case studies. An example of such an improvement is the expansion of the MET matrix into a METES matrix: Material, Energy, Toxicity, Economy and Social aspects (Fig. 6). The socio-economic sustainability assessment in the SSbD framework requires a structured approach. Beyond that, it is of interest to test LCBROM for that purpose since the dialogue with involved parties at an early stage provides a platform to address topics beyond environmental issues. Such an expansion of the matrix may increase the involvement of other actors who do not necessarily contribute to technology development but can have an interest. Examples of such actors are independent experts, authorities setting regulations, the

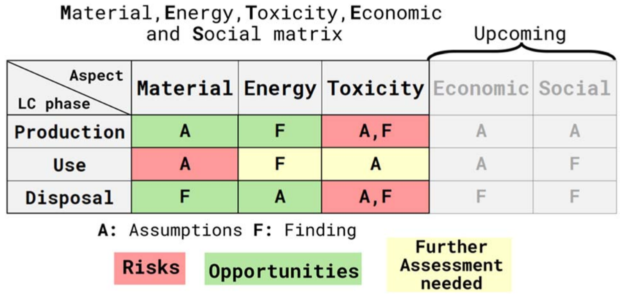

Fig. 6 LCBROM matrix extension including economic and social categories.

general population and even competitors. The revised SSbD framework proposes a selection of indicators that address social fairness, competitiveness and societal life cycle costs and can be explored based on publicly available data.[5]

As with many other environmental assessments, it is challenging to summarize the results in a way that is easy to communicate. As of now, the documented result of an LCBROM is the MET matrix. To facilitate communication, the information written in the matrix must be self-explanatory in the sense that the reader should not have to consult the bulk text of the report to understand the results. Alternative ways of presenting the results from an LCBROM must be investigated to further improve its accessibility and understandability for non-experts.

The extended LCBROM matrix is suggested as a suitable format to capture the traditional sustainability pillars. But other aspects can also be added to the matrix, such as politics or legislation. A parallel can here be drawn to the PESTEL framework—covering Political, Economic, Social, Technological, Environmental, and Legal factors—which offers a structured way to analyse external influences and can inspire further development of the MET matrix by integrating broader contextual dimensions.[28] The term traces back to 1967 when Aguilar presented ETPS (Economic, Technical, Political, and Social) in his book Scanning the Business Environment.[29] Later, other practitioners added Environmental and Legal aspects as additional entities.

Beyond Mistra TerraClean, the LCBROM method is being revised and tested in the EU-funded research programmes BiOSusTex, with a focus on new chemical raw material and process developments for the textile sector (https://www.biosustex.eu/), and Bio-LUSH, with a focus on using fibers from underexplored European plant resources in biobased products (https://biolush.eu/).

Conclusions

In this article, we propose a qualitative screening approach that can be used to support SSbD assessments. It may be used as an initial step of an SSbD assessment to facilitate its scoping process. Additionally, the tool can be used in the environmental sustainability assessment in early innovation when there is not enough data to perform a quantitative LCA.

The method offers a structure that facilitates the identification of the most relevant issues comprehensively without conducting an extensive assessment. It requires a collaboration between several different experts and can be applied to most technology fields with relatively low costs in terms of time and money.

LCBROM has been successfully applied in four case studies to materials and technologies that are in the early stage of innovation. The main learning from its development and application is the importance of having a state-of-the-art benchmark and/or a specific case to relate the innovation to for opportunity identification. If no such reference is established, opportunities can only be identified by considering a scenario where no action is made at all.

Author contributions

Conceptualization: Jutta Hildenbrand and Tomas Rydberg, data curation: N/A, formal analysis: Therese Kärnman, Steffen Schellenberger, Marie Gottfridsson, Kristin Johansson and Jutta Hildenbrand, funding acquisition: Maja Halling, Tomas Rydberg and Jutta Hildenbrand, investigation: Therese Kärnman, Steffen Schellenberger, Marie Gottfridsson, Kristin Johansson and Jutta Hildenbrand, methodology: Therese Kärnman, Steffen Schellenberger, Marie Gottfridsson, Maja Halling, Kristin Johansson, Tomas Rydberg and Jutta Hildenbrand, project administration: Maja Halling, resources: N/A, software: N/A, supervision: Maja Halling, Jutta Hildenbrand and Tomas Rydberg, validation: Therese Kärnman, Steffen Schellenberger, Marie Gottfridsson, Kristin Johansson and Jutta Hildenbrand, visualization, Steffen Schellenberger and Therese Kärnman, writing – original draft: Therese Kärnman, and writing – review & editing: Steffen Schellenberger, Marie Gottfridsson, Maja Halling, Kristin Johansson, Tomas Rydberg and Jutta Hildenbrand.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information: schematic description of the structured development of LCBROM, a non-exhaustive list of guiding questions to support LCBROM discussions, and questionnaire 1 and 2. See DOI: https://doi.org/10.1039/d5su00930h.

Acknowledgements

We thank Mistra for funding the research programmes Mistra TerraClean II (2015/31) and Mistra SafeChem (18/11), as well as the European Commission for supporting BioSusTex (No. 101135372) and XPRES (Initiative for Excellence in Production Research). We gratefully acknowledge Hanna Holmqvist for inspiring the LCBROM methodology and Olga Lysenko, Sahar Safarianbana, and Nilay Elginoz Kanat for their contributions to the social and economic section of the METES matrix. Special thanks to Nilay Elginoz Kanat at the IVL Swedish Environmental Research Institute for the initial external review. The article title is based on a presentation at the SETAC Europe 35th Annual Meeting.

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