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Integrating Life Cycle Assessment and Environmental Risk Assessment: A critical review

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ABSTRACT

Life cycle assessment (LCA) and Environmental risk assessment (ERA) are highly complementary; several studies have attempted to bridge the two approaches by means of integration for a more comprehensive assessment of environmental impacts. This paper reviews existing studies on LCA and ERA integration to establish an understanding of the benefits and challenges of different integration approaches and provide suggestions for future approaches for integrating LCA and ERA.

A total of 36 reviewed studies employed a variety of approaches and used different indicators in reporting the results of the integrated assessment, making direct comparison difficult. The most common integration method is the subset integration, and 17 of the reviewed studies employed this approach. 1 out of all the reviewed studies used a parallel integration, while the remaining studies employed other approaches including “complimentary use”, “sequential” and “multi-option”. Some of the reviewed studies were case study specific, while others employed a methodological approach, but most of these studies did not present the procedure for integration.

Common barriers to integration of LCA and ERA include the lack of data (e.g., on toxicity) and differences in model structure of LCA and ERA. The majority of the proposed approaches presented in the reviewed studies are inclined towards one of LCA or ERA, resulting in the omission of important components from the other, and leading to the inability of these approaches to address properly the needs of both LCA and ERA simultaneously. There is no clarity on the available information or data required to progress in this area and a clear pathway for practitioners to follow when integrating LCA and ERA, is lacking.

A comprehensive approach that provides opportunity to address both LCA and ERA objectives, based on case study needs, is required to harness the benefits of integrating LCA and ERA. This should be built around the theories and principles of both tools to encompass all relevant impacts and risks and to ensure complementarity. A conceptual framework that provides flexibility for modifications, to suit relevant case studies, would provide direction to practitioners on the general concepts to adopt, and ensure consistency in the overall approach of integrated LCA and ERA.

Keywords: Life cycle assessment, Environmental risk assessment, Integration, Combination

1. Introduction

All human activities have a potential impact on the environment. These impacts are exacerbated by the production, use and disposal of products, for example, food, medicines, consumer products or infrastructure (Liu et al. 2012; Rebitzer et al. 2004). Environmental policies and practices designed to prevent unacceptable environmental impacts should be based on a comprehensive assessment that includes consideration of the inherent properties of the chemical constituents of products and their potential adverse ecological effects. Properties of the environmental compartments potentially exposed and the likelihood of exposure, as well as resource consumption, emissions and waste, should all be considered (Hauschild et al., 2009; Kobayashi et al., 2015). There is no single tool that covers all these aspects, but a combination of life cycle assessment (LCA) and environmental risk assessment (ERA) could provide the information required (Flemstrom et al., 2004; Tsang & Sonnemann, 2018).

LCA evaluates possible environmental impacts aggregated over the entire life cycle of a product (Finnveden & Morberg 2005; European Union 2010a). It facilitates decision making processes by allowing a quantitative comparison of the environmental impacts of alternatives. ERA is a formal process for integrating information on the fate and behaviour of chemicals in the environment with information on their effects on ecological systems in order to evaluate the likelihood of adverse environmental impacts (i.e. environmental risk) (Maltby 2006). LCA and ERA address different aspects of the overall environmental impact of products and employ different assumptions and procedures. The two techniques may therefore result in apparently conflicting outcomes resulting in incomplete, confusing or misleading information to policy and decision makers (Kobayashi et al., 2015; Harder et al., 2015).

One way to address this challenge is to combine LCA and ERA into a single assessment approach that integrates the benefits of both approaches. Several attempts have been made to combine LCA and ERA, however, approaches used in integrating these two tools varied widely, with fragmented information and/or data to progress in this field.

A number of studies have reviewed the work carried out in the field of LCA and ERA integration. These studies focused on different aspects related to assessment of environmental impacts, and most of the studies focused on actual case studies blending LCA and ERA (Harder et al. 2015) or integration in a specific context for example; contaminated site remediation (Morais & Delerue-Matos 2010), or mineral waste reuse scenarios (Benetto et al., 2007), rather than the actual methodologies. Some studies [e.g., (Herva & Roca 2013)] reviewed work on LCA and ERA integration, but this was not the main focus of the study. A generic review of methods for integrating LCA and ERA was carried out by Flemstrom et al (2004), describing some methodological approaches of combining the two tools. The review presented possible ways in which LCA and ERA can be integrated, however, since publication in 2004 further relevant papers have been published. More recently, Kobayashi et al (Kobayashi et al., 2015) also focused on methodological aspects, but the review lacks theoretical details and analysis of the presented methodologies. Only a few of these studies highlighted the actual reason for integrating LCA and ERA, and some did not clearly present research gaps in this area, nor a way forward. A more critical review and information on existing integration approaches is required to understand the need for integrating LCA and ERA, the effort made so far, and what is still lacking in this area. Here we provide a critical review of the progress and current status of integrating LCA and ERA. The specific objectives of the review are:

- To evaluate the advantages and disadvantages of existing methods of integration of LCA and ERA;
- To establish an understanding of the barriers to integrating LCA and ERA and provide recommendations for future integration approaches.

2. Use of LCA and ERA in assessing environmental impact

2.1. What are LCA and ERA?

LCA analyses the potential environmental impacts of a product over the entire life cycle. It has been standardized by the International Standards Organization (ISO): ISO 14040 and ISO 14044 (European Union 2010b) and involves the quantification of all resources used and emissions associated with a product's life cycle, with reference to a functional unit. The quantified resources and emissions are collated to form the life cycle inventory (LCI). The LCI is further analysed in the life cycle impact assessment (LCIA) stage.

LCIA uses characterisation models to convert the elementary flows from the LCI stage into emissions and impact categories (e.g., global warming or acidification potential), that enable comparison of the diverse environmental effects (European Union 2010a; Finnveden and Morberg 2005). For each category of impact, the impact assessment applies a substance-specific characterisation factor (CF), which represent the substance's potency (i.e., its specific ability to contribute to the impact category):

$$CF_j = \sum_i CF_{ij} = \sum_i M_i \cdot W_{ij}$$

Where M_i is the amount of emission i released, W_{ij} is the characterization factor for the emission i within the category j, CF_{ij} is the contribution of the emission i to the category j, CF_j is the characterized value of the category j.

ISO 14044 recommends that CFs and the models to derive these factors (characterisation models) are based on an international agreement or approved by a competent international body. For example, in the case of greenhouse gases, the global warming potential (GWP) developed by the Intergovernmental Panel on Climate Change (IPCC) is normally used as the CF for the climate change impact category.

In a risk assessment the potential hazard and likely level of exposure are analysed. Environmental risk assessment considers risks to humans and ecological systems whereas ecological risk assessment focusses on non-human populations, communities and ecosystems (Maltby 2006). ERA is used to establish whether risk management is needed in order to avoid the unacceptable environmental impact of chemicals and other stressors (ECETOC 2016). For example, a substance specific risk assessment is a regulatory condition for market authorisation in Europe (Benetto et al., 2007). The risk assessment is usually carried out in a tiered manner based on the tonnage, use and hazards of the substance.

Chemical ERA includes problem formulation, analysis of exposure and effect, risk characterization and generation of information to inform risk management. Problem formulation is the articulation of the focus of the risk assessment – what is being protected, how will impacts be assessed and what level of impact is acceptable. Next an analysis of information on the environmental fate and behaviour of chemicals in the environment (i.e. air, water and land) is integrated with an analysis of information on potential effects on organisms likely to be exposed in those environments. This effects assessment includes direct toxicity, indirect effects mediated by species interactions (e.g. competition, predation) and effects due to secondary poisoning via trophic interactions. Risk is then characterised by comparing the predicted or measured environmental concentration to the predicted no effect concentration. This information is used by risk managers to assess whether risks are acceptable or can be mitigated. ERA employs the threshold approach, where certain thresholds values of a given pollutant in an environment must not be exceeded (ECETOC, 2016).

Figure 1a and b show the frameworks used for LCA and ERA respectively.

2.2. Comparison between LCA and ERA

The relationships, differences and potential integrations between LCA and ERA have been analysed and reported by other researchers (Hauschild & Potting, 2006; De Haes et al., 2006; Flemstrom et al., 2004; Harder et al., 2015) and a comparison of the fundamental elements of LCA and ERA are presented in Table 1 (Breedveld, 2013).

LCA focusses on environmental loading and considers the system's total use and release of toxic and non-toxic substances, while ERA is receptor focused and considers quantitative emissions of substances to the environment. ERA considers actual ecological impacts, while LCA considers contributions to categories of environmental stressors (e.g., global warming potential, acidification potential). In other words, LCA uses the attributional mode of assessment while ERA uses the full mode of assessment (De Haes et al, 2006).

ERA compares the exposure of ecological systems to specific stressors (e.g. single chemical, chemical mixtures or multiple stressors) in a specified environmental scenario, usually realistic worst-case. The assumption being that if the realistic worst-case is acceptable then other environmental scenarios will also be protected. In contrast, LCA takes a comparative approach of environmental performance for different products under routine operations and steady state condition (Flemstrom et al., 2004; Harder et al., 2015). This implies that a typical LCA overlooks the time and space distribution of environmental stressors, spatial and temporal variation in the structure and functioning of ecosystems and the implications of interspecific variation in the vulnerability species to specific stressors. It also ignores differences in near and far field effects, and regional variation in the acceptability of impacts or toxicity thresholds. LCA usually does not include background concentrations and cannot therefore address threshold issues or actual quantification of risk. However, LCA is more effective for calculating the potential for marginal risks for a larger number of stressors and emission locations (Bare, 2006).

The scaling up to a functional unit, the use of linear-dose response relationships and the absence of temporal and spatial elements in LCI data, limits the capacity of an LCA to predicts actual impacts, hence impacts in LCA are considered potential impacts (De Haes et al., 2006; Hauschild & Potting, 2006). The inability of ERA to account for secondary emissions and the resulting effects elsewhere (i.e., outside of the specific area being assessed), limits its application in forming a theoretical basis for deciding on the most sustainable options when comparing alternative products or services.

With regards to toxicity assessment of chemical pollutants, improved accuracy of assessment outcome is achieved with ERA due to the use of specific exposure and effects data. LCA generally uses average global or regional data (Kobayashi et al., 2015) or best estimates, and assumes linear relationships between inventory flows and environmental responses, for assessment of impacts (Hauschild & Potting 2006). Although, it can be argued that LCA is not directly concerned with environmental risks, but with relative comparisons between product systems, hence, there is no need to use worst case estimations.

2.3. Rationale for integrating LCA and ERA

In environmental management systems, LCA is useful in assessing impacts on a global (macro) scale while ERA is useful in assessing impacts on a local (micro) scale (Liu & Ramirez 2018; Kobayashi et al., 2015; De Haes et al., 2006).

Studies have demonstrated potential burden shifting and likely trade-offs between the local and global impacts. For example, a study by Liang et al (Liang et al., 2013) found the potential of problem-shifting between global and local impacts in biodiesel production depending on the type of feedstock used. Algae derived biodiesel indicated higher global warming potential while waste cooking oil derived biodiesel showed increased human toxicity. The low global impacts can be attributed with reduced burden of feedstock production when using waste cooking oil, whereas the risk of toxic chemicals releases may be attributed to the oil composition, which remains a subject of concern in the field of risk assessment (Pikula et al., 2019). Therefore, outcomes from LCA and ERA sometimes suggest opposing solutions for the same environmental problem. A similar case of trade-offs between LCA and ERA was demonstrated for contaminated site remediation (Morais & Delerue-Matos 2010), where the focus is primarily on local risk reduction without consideration of secondary impact of risk mitigation measures. For the case of sewage treatment the local risk of chemicals and pathogens can be significantly reduced but at an increased energy cost of advanced technologies (Harder et al. 2015). Such burden shifting increases the limitations of individual assessment (LCA or ERA) to appropriately inform policy making related to a product or service (Tsang & Sonnemann 2018; Kobayashi et al., 2015). Hence, to genuinely reduce impacts and avoid problem-shifting between local and global spaces, both aspects should be considered concurrently.

Toxicity indicators for human health effects and ecosystem quality are essential in both ERA and LCA. Although toxicity effects of chemical pollutants are a more central focus of ERA, chemicals in industrial use are numbered in the tens of thousands and any of them can, in principle, occur in the emissions inventory for a product, hence, the inclusion of toxicological and ecotoxicological impact assessment methods in LCIA has been for many years of great interest to LCA practitioners (Flemstrom et al., 2004; Guinée & Heijungs 1993; Saouter et al., 2017).

In line with this, several methodologies that account for fate, exposure and effects of chemical substances have been developed including IMPACT 2002 (Jolliet et al. 2003), USES-LCA (Huijbregts et al. 2000), Eco-Indicator 99 (Goedkoop et al. 1998) and CalTOX (Hertwich et al. 2001). These methods follow the approach normally taken in chemical risk assessment, employing environmental multimedia, multi-pathway models to account for the environmental fate and exposure processes, and the effects that exposure may have on human health or on the health of ecosystems. Others, such as EDIP (Hauschild & Wenzel., 1998), rely on key properties of the chemical to account for fate and exposure (Rosenbaum et al., 2008). However, differences in methodologies have resulted in failure to properly address toxicity impacts in LCIA (Flemstrom et al., 2004; Guinée & Heijungs 1993; Pant et al., 2004) which can be attributed to the varying toxicity characterisation score yielded by different methods for a given substance. The difference in scope among these methods, the modelling principles applied and characterisation factors (CFs) they generate (Hauschild et al. 2009) all contribute to variations in the results of assessment.

In 2002, the UNEP-SETAC international life cycle partnership (Jolliet et al. 2004) launched a task force on toxic impacts, with the aim to develop and disseminate practical tools for evaluating the opportunities, risks, and trade-offs associated with products and services over their whole life cycle. The "USEtox" method was produced (Rosenbaum et al., 2008), which represents a consensus based method of characterising the toxic impacts of chemical emissions in LCIA. It employs a multimedia-box approach to characterize the toxicity-related impacts of chemical emissions on freshwater ecosystems and on humans.

Unlike in traditional LCIA (see section 2.2), CFs for assessment of toxic impacts are calculated from the combination of matrices containing fate factors (FF) in days, exposure factors (XF) in day^{-1} (for only human toxicity), and related to freshwater compartment w, and effect factors (EFs) in cases/kg intake for human or PAF m3/kg for ecotoxicity, and the results in specific CFs in cases/kg emitted, as shown in Equation 2. PAF - potentially affected fraction of species.

$$CF_i = FF_{i,w} \cdot XF_w \cdot EF_w$$

Incorporating the fate and exposure factors accounts for the dynamic behaviour of different substances in different media. Although USEtox is considered a reference model among practitioners with regards to toxicity assessment in LCA, data related issues such as the scope (substance coverage) and reliability, seems to affect total dependency on the USEtox factors (Saouter et al., 2017).

Toxicity characterisation factors are heavily based on ERA models (Flemstrom et al., 2004; Pant et al. 2004). Nevertheless, other important ERA related questions are often left unanswered and ERA practitioners generally see this approach as not sufficient to quantify for example human health risk associated with chemical pollutants.

Integrating LCA and ERA is expected to provide a more holistic assessment of environmental impacts and has the potential to save time and cost of assessment.

3. Methodology for critical review

3.1. Literature search strategy

A literature search of existing studies on combining LCA and ERA was conducted using the scientific search engines Science Direct and Google Scholar. The full names and acronyms for LCA, ERA and RA (category 1) were combined with the keywords; integration, combination, and hybridisation (category 2) to search for studies that employed both LCA and ERA in the assessment of environmental impacts. Searches were repeated replacing integration with integrating and replacing combination with combining and combined. The OR Boolean was utilised to allow multiple searches at the same time. The literature search yielded 918 articles, which were screened using the process described in Figure 2.

The first stage of screening focused on the title and abstract as shown in Figure 2. For the following stage of screening, studies that contained information on only LCA or ERA individually were not considered for the critical analysis of integrated assessments, but some of the studies for example, those describing the methods and principles of the individual tools, were utilised in providing the background for the review study. Since most of the literature on integrating LCA and ERA are concentrated from the year 2000 onwards, only studies that were published since the start of 2000 were found most relevant.

A total of 36 articles, including 6 reviews, met all the selection criteria and were evaluated in detail. The selected studies are summarised in Table 2 and Table S1 (see supplementary materials) which contains information on the approach and methods employed by the studies to integrate LCA and ERA, the indicators used to present results of integrated assessment, key findings and research gaps. Studies are classified as either 'parallel' (i.e. results are combined from separate LCA and ERA) (**Figure 3**), 'subset' (either LCA as a subset of ERA or vice versa) (Flemstrom et al,2004) (Figure 4) or 'other' which includes the complimentary approach and integration approaches that do not fall within the two general classifications.

In analysing the selected studies, comparison was carried out in terms of clarity, usefulness and flexibility of the integration methods. Comparison among studies is important, however, most of the reviewed studies had no comparable extractable data, hence the opportunity for meta-analysis was limited. Following on from previous reviews carried out on integrating LCA and ERA, this paper also analyses progress in the different integration methods and evaluates the current state of integrating LCA and ERA.

4. Results and Discussion

4.1. Previous work integrating LCA and ERA

As shown in Table 2 (see also Table S1 in supplementary information), the studies collected for the critical review are widely varied in terms of the overall concept used to combine the elements of LCA and ERA in their respective assessments. For example, Nishioka et al. (2005) incorporates regional variability in emissions and exposure into inputs and outputs of LCA, which allows the identification of probabilistic causal linkage between environmental stressors and receptors in a given population. The use of location weighted intake fractions was suggested by the authors as a way of addressing the difficulty of incorporating regional exposure in LCIA. While several benefits including reduction in health impacts were demonstrated in the study, the absence of upstream impact (including economic consequences) of the additional insulation required for end-use energy reduction in the buildings limits the scope of the assessment. Milazzo & Spina (2015) assessed the human health risk in a biodiesel production chain, by incorporating modified models from RA into LCIA to determine risks and impacts on a variable scale. Another study by Nishioka et al (2006) extended an existing framework developed for combined input-output LCA and RA for public health impacts from particulate matter, to also address greenhouse gases and the public health consequences of changes in income. However, a high level of uncertainty resulted in the need for modification of this approach.

Research has been carried out in an effort to develop a more systematic approach of integrating LCA and ERA; Herva et al (2012), developed an eco-design tool using fuzzy logic where the outputs from LCA, ERA and Ecological footprint (EF) were combined to evaluate the environmental performance of beverage bottles made from poly vinyl chloride (PVC) and polyethylene terephthalate (PET). Although this was a simplified and interesting multi-criteria approach of combining LCA and ERA, the tool was sensitive to changes in Ecological Footprint (which includes LCA indicators such as GWP and AP), only when some ERA indicators such as cancer risk factor (CR) and hazard quotient (HQ) were low enough. This approach demonstrates some degree of reliability in addressing the needs of RA and LCA in the given case study, however, not incorporating LCA and ERA at initial assessment stage reduced the flexibility of assessment and opportunities to identify and manage potential trade-offs. A more balanced structure of the eco-design tool, such as expanding the number of levels for the risk indicators and also allowing the tool to pick up important indicators from LCA and EF, can avoid the generation of misleading results. Further work by Liu et al (Liu et al., 2012) also employed the fuzzy based approach at the initial assessment stage, to evaluate effects of pollutant releases from a recycling plant. Incorporating the LCA concept to identify the source-pathway-receptor-impact relationship, was useful in determining the significance of midpoint effects, but the study lacks strong theoretical elements of LCA, and the assessment tends to be heavily subjective.

Earlier programmes such as the European Union (EU) funded OMNITOX and DANTES (Flemstrom et al., 2004)(Benetto et al., 2007), have attempted addressing the issue of integrating LCA and ERA. These projects focused on different aspects, for example, OMNITOX focused on toxicity assessment in LCA, by focusing on the development of CFs for use in LCIA. LCA toxicity assessment models including USES-LCA, CalTox, and EDIP characterisation were all accepted within the OMNTOX project. However, most of these projects were faced with practical challenges related to data (e.g., substances toxicity information) and compatibility of model structures of LCA and ERA, and variations in output of assessment from different models (see section 2.3). Hence, the practicality of integrating the elements of these tools remains a top agenda for both LCA and ERA practitioners.

4.2. Comparison of LCA and ERA integration methods

Of all the reviewed studies, only one study (Linkov et al. 2017) focused on the parallel approach of integration, whereas 6 and 11 of the reviewed studies focused on LCA as a subset of ERA and ERA as a subset of LCA respectively. The former involves the application of life cycle thinking within ERA (Shih & Ma, 2011; Harder *et al.*, 2015), i.e., extending the traditional ERA of one substance and one central site to multiple substances and from different sites within a product's life cycle (Figure 4). The latter involves the incorporation of ERA elements such as site-specific fate and exposure models within the wider boundary of an LCA (Figure 4). The remaining 18 studies employed either complimentary or non-conventional approaches.

4.2.1. Parallel Integration

Many studies have performed separate LCA and ERA for the same case study, however, most of these studies did not formally combine the outputs of the assessments. Only one study (Linkov et al. 2017) among the reviewed studies was found to proposed the parallel method of integrating LCA and ERA. In reality, most of the complimentary approaches reviewed in this study are based on individual assessments. However, the procedure of some integration methods such as the "multi-option" (Tsang & Sonnemann, 2018) and "**s**equential" (Barberio et al. 2014) approaches, did not align with the overall concept of parallel integration. Parallel integration involves separate individual assessment for the same case study, followed by a combined analysis of output, using decision analysis tools.

Parallel integration has the benefits of reducing the complexity and uncertainty that comes with combined assessments. Linkov et al. (2017) highlighted that in the context of nanotechnology, a systematic combined analysis of output from individual assessments is best because of the practical difficulty and lack of data for integrating LCA and RA at the methodological level. Despite these advantages, the complimentary benefits of combining the two tools have been demonstrated in many fields as the results of individual assessment can sometimes disagree (Kikuchi & Hirao, 2008) which often complicates the decision making process.

Parallel integration can be applied depending on the need of the assessment, for example, in complex systems, it may be more realistic to use the parallel integration approach, depending on the availability and reliability of data for a combined assessment.

4.2.2. Subset Integration

The great majority of the reviewed studies employed the subset approach, either by inclusion of ERA into LCA (e.g., toxicity assessment in LCA), or life cycle thinking in ERA, where ERA is the central tool, but the assessment is based on the life cycle perspective, allowing the assessment of risks along their entire life cycle of product systems, from design to end of life. For example, Kuczenski et al (2011) modelled toxic flows in the life cycle of a child's plastic (PVC) toy containing dibutyl phthalate (DBP) as plasticizers. The study utilised risk and toxicity data reported by three hypothetical agents, where the focus was on the DBP across the main stages of the product life cycle, including manufacturing, use and end of life. This approach is useful in tracking toxicants and communication of risk and hazard information related to a product. However, it is not clear whether the assessment included the impact of other resources and emissions related to the product's life cycle.

The incorporation of LCA within the risk assessment can take different dimensions and different terminologies are used to refer to this type of integration approach, for example, life cycle risk thinking, life cycle risk assessment, risk-based life cycle assessment, life cycle-based risk evaluation and life cycle risk management have all been used to describe LCA as a subset of ERA. Likewise, the LCA based integration varied across the reviewed studies, including risk informed LCA, toxicity assessment in LCIA, or estimating the probabilistic measure of potential hazard along the life cycle of the product.

The most common of the subset approach is the inclusion of ecotoxicological and toxicological parameters in the life cycle impact assessment (LCIA) of an LCA, which can be performed using a number of well-known impact assessment methods e.g., IMPACT 2002 (Jolliet et al. 2003). Data generated from RA are very useful in the assessment component of LCA, especially toxicity (Guinée & Heijungs, 1993). Although it is also possible to compare local and global impacts within an LCA framework, for example, the application of LCIA models to local pollutants, the relevance of including site-specific assessment models to account for local impacts in an LCA was recognised in some studies including contaminated site remediation e.g., (Morais & Delerue-Matos, 2010) and metal degreasing e.g., (Kikuchi & Hirao, 2008).

Harder et al (2015) categorised the subsets approach into three different clusters including: 1) site-dependent assessment which communicates regional risks and impacts; 2) the site-specific assessment that communicates local risks and impacts and 3) trade-offs or local and global effects, which comprises of three different groups of site-specific and site-generic assessments. The classification of LCA and ERA integration based on different levels of spatial differentiation was also reviewed by De Haes et al (2006). Although the increased spatial differentiation in LCA and the use site dependent or site-specific pollutant characterization factors obtained by detailed models might have been used in some of the studies claiming integration of LCA and ERA, but in practice integration did not take place. In most cases, this approach improves the accuracy of assessment through generation of a more realistic scenarios within the LCA. Additionally, most site-dependent models in LCIA are related to specific geographical contexts, such as Western Europe (e.g., EDIP97, IMPACT2002+), United States (e.g., US EPA TRACI) (Morais & Delerue-Matos, 2010). The application of models that are not relevant to a specific regional context, can result in reduced reliability of results. Hauschild et al (2006) described the 3 levels of spatial differentiation in LCIA as site-dependent, site-specific and site-generic.

4.2.3. Others

Those studies employing a complimentary approach, but somehow in a parallel context, i.e., in between the two approaches e.g., (Liang et al., 2013; Socolof & Geibig, 2006), were grouped together with other approaches that have not been discussed in previous studies. Integration approaches such as the multi-option (Tsang & Sonnemann, 2018), the sequential (Chen et al., 2012) and the adaptation mode approach (Loiseau et al. 2013), were put in this category as they did not fit with the parallel or the subset approaches. Most of the studies in this category are case study specific. When exploring a concept of integration, it is important to align the key questions that LCA and ERA intend to answer with the specific goals of the case study.

4.3. Type of study employed in integrated assessments

From Table 2 (see also Table S1 in the supplementary information), the “type of study” used in context differs from the integration approach employed in the reviewed studies. This means that a study can be focused on LCA (i.e., LCA-based) and employ any of the integration methods. Figure 5 shows the total number of reviewed studies that are LCA-based or ERA-based. There are more LCA related studies employing the elements of ERA, in order to broaden the scope of assessment, to cover the toxic effect of chemicals (Pizzol et al. 2011), or estimate the associated risks (Herva et al. 2012). Some of these studies were also found to be focused on the use of frameworks or models (Galante & Haddad 2014), however only a few showed actual procedure for the proposed integration approach. This can be attributed to difficulty often experienced in combining the two tools at the initial assessment stage.

The ERA-based studies are largely case study related, for the simple reason that a specific risk assessment is often focused on a given site, substance or mixture of substances. Some of the studies however presented frameworks and models (Liu et al. 2012).

4.4. Indicators used in integrated assessments

Several of the reviewed studies presented end point toxicity indicators such as human health (HHI), ecotoxicity (ET) [e.g., (Pikula et al. 2019; Milazzo & Spina 2015; Kikuchi & Hirao 2008)] or risk related indicators including the risk ratio in terms of predicted environmental concentration (PEC) to predicted no effect concentration (PNEC). Studies that focused on actual methodological approaches (i.e., framework and models) are more likely to use toxicity related indicators (Milazzo & Spina 2015). Although studies [e.g., (Benetto et al., 2007)] have made efforts to develop and report outcome of combined assessment using uniform indicators, the indicators used in individual assessment are not easily integrated into the other. For example, qualitative indicators used in risk assessment are not easily integrated into LCA indicators.

In general, LCIA is more comprehensive in covering a larger number of impacts than RA and can include smog formation, acidification, eutrophication, human health, ecotoxicity, radiation, fossil fuel depletion, land use and water use. In principle, LCIA should also include categories such as noise, human fatalities due to accidents, indoor air pollution, and many other issues (Bare 2006). However, accounting for the latter indicators in a traditional LCIA is often difficult as a result of limitations in developing appropriate characterisation factors. A summary of the most common indicators employed by the reviewed studies, is shown in Figure 6, based on the number of studies that employed the specific indicator. Some studies [e.g., (Tobias et al., 2017; Breedveld 2013)] did not present specific indicators, and only described procedures for integration without specific assessment examples.

Combined indicators used in this context (Figure 6) refer to those representing both risk and impact (global and/or local) or only global and local impacts without risk related indicators. Indicators such as PEC, PNEC, HQ, and Risk (carcinogenic or non-carcinogenic) are grouped as risk related indicators. The common indicator used to represent impacts for both LCA and ERA is the human health impact (HHI), since when dealing with toxicity of chemicals/pollutants, a common point of concern is the impact on human health. Some studies utilised probability elements in their assessments, for example, Liu et al., (2012) incorporated both probabilities and impacts in their combined assessment, but difficulty often arises when dealing with specific indicators (e.g., GWP) due to data limitation, and related ambiguity.

Development of uniform indicators is important in integrated LCA and ERA, however, the question that arises is whether we have enough information to develop appropriate combined indicators and the corresponding units to express these indicators? The model USEtox developed for toxicity assessment in LCA, uses the unit CTU to express both human toxicity impact (as CTUh) (i.e., increase in morbidity (the number of disease cases) in the total human population per unit of mass of the chemical emitted), and ecotoxicity impacts (as CTUe) (i.e., the estimated PAF integrated over time and the volume of the freshwater compartment, per unit of mass of the chemical emitted) (Rosenbaum et al., 2008). Which substitute the use of a reference substance (e.g., the CO_2 for GWP, kg 1,4 dichlorobenzene (DB) for toxicity) employed in conventional LCAs. Nevertheless, more work is required to enable reporting of these indicators with a probabilistic measure and standardisation of combined indicators is particularly of importance in this context.

4.5. Terminology used in integrated assessment

Various terminology has been employed to describe the combined use of LCA and ERA, including “integration”, “combination”, “hybridisation” and sometimes “incorporation”. Some of these phrases are analysed by other researchers (Harder et al., 2015) as referring to different things. Authors discussing topics like integration and/or combination of LCA and ERA, may refer to at least two quite different things: adopting and applying ERA knowledge and/or data in LCA (particularly LCIA).

In combining LCA and ERA, both aspects need to be properly addressed. Focus on local risk mitigation measures without consideration of the life cycle impacts of these measures may result in shifting of the effects elsewhere. The inclusion of emissions resulting from these sources across a product's life cycle chain is essential in addressing both LCA and ERA perspectives. The procedure and degree to which specific components of the individual tools, are considered in an assessment can provide more insight into the terminology to adopt for the specific case. A large number (13) of the reviewed studies used the word "integration/integrating", 8 studies mentioned the word "combination/combining", 2 of the studies used "hybridisation" while the word "incorporation", "adaption" and "blending" were employed in at least one study each. The remaining 12 studies did not mention any of these terminologies particularly those studies related to specific case studies.

The use of the term "integration" as a search term may have identified papers that integrated LCA/ERA as the word could be applied to many things such as changes made within one of the individual tools, for example when integrating the space and time differentiation in LCA (Socolof & Geibig 2006), or when integrating the concept of toxicity impact in LCA, often the term "integration" is used. Employing a unified terminology will reduce misinterpretation in the context of complimentary use of LCA and ERA. Among all the terminologies employed, integration seems to be more appropriate in describing the simultaneous use of LCA and ERA, in which a balance is clearly established between the goals of the two tools. Other terminologies such as hybridisation or incorporation can also be used when adopting some elements (e.g., knowledge or specific set of data) of ERA into LCA or vice versa. The term "combination" can also be used when employing both LCA and ERA separately, with or without necessarily analysing the individual output simultaneously.

4.6. Benefits and limitations of existing integration methods

Table 3 shows the benefits and limitations of the LCA and ERA approaches reviewed. Although studies categorised integration approaches using different terminology, there is sometimes no distinct difference between them. For example, the "LCA as screening" and "Life-cycle QRA" (quantitative risk assessment) (i.e., LCA as a subset of ERA) reported by Kobayashi et al (2015), are technically the same, or we can say that the screening part is also part of the subset approach.

This LCA as a subset of ERA approach, has been described as advantageous in assessing the sustainability of emerging technologies (Socolof & Geibig 2006). It offers a systematic approach to identify risks of innovative technologies along the life-cycle of a product or process system (Breedveld 2013). Unlike the conventional ERA method or the parallel integration of LCA and ERA, employing life cycle thinking in risk assessment can provide information for the early assessment of potential impacts on health, safety and environment, so that products are designed in such a way that modifications can be carried when negative impacts are identified. One notable benefit of this integration approach is the reduced time and cost of assessment as it helps to streamline the number of assessment stages. However, in most cases the LCA scope is often narrowed, and the assessment does not look at the cradle to grave system boundary of the specific substance under consideration, but assesses the risk associated at specific stages of the product life cycle.

A combination or integration is achieved only when both LCA and ERA perspectives are properly addressed in a given case study. Often the main area of interest for combining LCA and ERA is in impact assessment, where the aggregated impacts of material flows are characterized. This makes sense in terms of developing technical compatibility between the two methodologies. However, it effectively narrows the scope of LCA to impact assessment alone.

Employing ERA as a subset of LCA is more widely used because of the importance of accounting for toxic impacts of chemical substances in LCIs. Like the LCA as a subset of ERA, this approach of integration also saves time and cost of assessment, and there is opportunity to report outcomes of assessment using a greater number of indicators. However, in most cases, risk related indicators are not reported as part of the results (Table 2), because most assessments of this kind are focused more on toxic effects without indicating the probabilistic measure or level of associated risk.

The complementary approach or other types of integration approaches provide ease of assessment by reducing the complexity associated with combined assessment (e.g., integration of model parameters, indicators, data etc.). They also reduce the risk of double counting or misinterpretation of assessment and show the individual strengths of both LCA and ERA. However, this approach can be time consuming, and may result in problem shifting and incomplete assessment, thus limited information for policy and decision-making process.

4.7. Challenges of integrating LCA and ERA

Previous attempts to integrate LCA and ERA have faced challenges resulting in limitations of the proposed approaches. The risk of double counting, inconsistencies in modelling choices, inadvertent inconsistencies in fate-exposure modelling and uncertainty and accurate determination of the probabilities are some of the potential pitfalls identified by Harder et al (2015). Milazzo and Spina (2015) encountered difficulty with the estimation of both the probability of the presence of the individual and the volume of the contaminated compartments, data for this is usually acquired from the hazard assessment and characterisation step in RA. Likewise, Liu et al., (2012) experienced difficulties when estimating the probability for some midpoint effects within the LCA impact indicators such as global warming, and the probabilities of impact from exposure to some pollutants. Other studies that encountered difficulties in combined LCA and ERA include Chen et al., (2012) in evaluating sustainability of waste water treatment (WWT) technologies and (Harder et al. 2014), in the assessment of the environmental of municipal WWT.

Combining LCA and ERA is a complex task; the methodological difficulty in blending the elements of both assessments has been the main barrier to successful integration. The process requires an in-depth understanding of the relationship between the two analytical tools. Harder et al (2015) proposed a design space to guide case studies blending LCA and ERA; the design space was used to evaluate the methodological differences of reviewed case studies on LCA and ERA integration. A similar design space was originally presented by Baumann & Cowell (1999), where they developed a framework to serve as a basis for comparing different environmental assessment tools. Three different aspects were considered in designing the framework, including, 1) generic aspects such as the specific tool or concept; 2) contextual aspects (including the goal behind the assessment, and the object under consideration); and 3) methodological context (i.e., issues considered, structural elements and data). The methodological context is considered more complex to deal with when it comes to integrating LCA and ERA, which indicates the need to understand the exchange of elements between the LCA and ERA and how this influences the corresponding output.

One of the main interests for LCA practitioners is accounting for the toxic impacts of chemicals in LCI; efforts in this area has been fairly successful, for example the USEtox (Rosenbaum et al., 2008) model is comprehensive and recommended by the EU for characterising toxicity related to human, aquatic and freshwater ecosystems (Saouter et al., 2017). However, difficulty in calculating effect factors e.g., for the freshwater compartment has been challenging due to large data gaps, substance coverage and related accuracy. The unequal representation of data points from different groups may introduce a bias in the estimation of the effect factor (Henderson et al., 2011). In the case of a specific metal toxicity e.g., chromium Cr(VI), currently, the USEtox model assumes the metal to remain in the same oxidation state, independent of environmental interactions, upon its emission in freshwater, whereas there are documented changes in the redox state of Cr(VI) emissions to freshwater (Hedberg et al., 2019). Hedberg et al., (2019) recommended integration of changes in Cr speciation in LCIA, and that the assessment should incorporate specific region of interest. Similar recommendation was highlighted by Bratec et al (2019) for the case study of bromine in soil. Thus, some of the CFs for ecotoxicity are classified as “interim factors” in the USEtox model. A more generic and dynamic approach that allows the flexibility of incorporating specific futures relevant to case study is therefore required.

Furthermore, scientific challenges such as near-field exposure and dose-response modelling, affect the human toxicity characterisation, for use in LCIA. In assessing the risk and impact of exposure to pathogens, Harder et al (2016) found that, occupational exposure and accidental exposure by children to sewage sludge at wastewater treatment facilities and on agricultural fields are not considered in the USEtox model, the model only considers exposure pathways originating in compartments at the continental and global scales. Improved assessment of exposure through capturing missing exposure settings and human receptor pathways, can be achieved by coupling additional fate and exposure processes in near field (consumer and occupational environments) with existing processes in far field (outdoor environments).

Effort has been made to advance toxicity assessment in LCA, to improve the aforementioned challenges, for example, (Fantke et al., 2018) working as part of the human toxicity task force (UNEP life cycle initiative), proposed a roadmap for advancing exposure and toxicity characterisation for use in LCIA. A set of specific questions addressing: a) approaches and data needed to determine human toxicity effect indicators for chemical emissions; b) the validity and maturity of such approaches and data needed to represent human toxicity impacts for currently missing pathways; and c) the relevance and feasibility of considering essentiality and long-term changes in the human toxicity characterization of metal emissions, were outlined in their scoping phase. The near-field and far-field approach was highlighted as a good starting point for accounting for toxic impacts in LCA, utilising this approach in a broader context presents even more opportunity to address some of the difficulties mentioned and provides a platform to bridge the asymmetry in models, knowledge and data.

4.8. A way forward

The extent to which the reviewed studies incorporate various elements of LCA and ERA differ widely with the objective and scope of each study. Studies that are inclined towards LCA are more likely to show the stages of the life cycle of the product under consideration while using the standard assessment procedure set by ISO14044 (European Union 2010a). A significant number of these studies however, showed only the impact assessment stage, skipping other stages such as the inventory development stage. This is perhaps because in an integrated assessment, whether LCA or ERA inclined, the focus is often on the toxic impacts of chemicals, hence, only a few studies [e.g.,(Liu et al. 2012)] included more assessment stages. Some of the ERA component stages, such as hazard identification and characterisation, were also omitted in many of the reviewed studies. A significant number of these studies assessed effect from potential exposure to specific substance [e.g., (Aramaki et al., 2006)(Milazzo & Spina 2015)].

Going forward, it is important for studies integrating LCA and ERA to focus on incorporating important components of LCA and ERA, to improve understanding of the link between the two methods and provide more insight into the variability in the fate and exposure-pathway characteristics of the substances considered. Since LCA and ERA aim to assess the global and local impacts respectively, outputs of integrated assessments expressed as impacts should be presented in a way that reflects these two aspects. This will improve comprehensibility, clarity and interpretation of outcome for decision making. Furthermore, advancing work on toxicity assessment of chemicals, such as development of characterisation factors for existing and new chemicals, is undoubtably essential in the given context, however, practitioners should see this as a way of deepening the scope of LCA. The toxicity assessment of chemicals should therefore be embedded as part of a bigger model that clearly recognises the need and provides pathways to address underlying local risks. To improve the robustness of any proposed approach, there should be a feedback element in the form of interactive link between LCA and ERA, to guide decision across assessment stages. A framework based on a combined near-field and far-field exposure assessment would enable both LCA and ERA perspectives to be considered simultaneously.

5. Conclusions

This critical review of 36 studies has demonstrated the complementary benefits of integrating LCA and ERA. Integrating LCA and ERA could potentially address some of the limitations presented in individual assessments. However, studies integrating LCA and ERA were found to be widely varied across different dimensions of assessment, which limits opportunity for retrieving useful comparable data from these studies. About half of the reviewed studies employed a subset approach of integrating LCA and ERA, and the remaining studies used other approaches generally categorised as “others”. Only one of the reviewed studies relates to parallel integration approach.

Data limitation on toxicity of chemical substances and incomplete information on relevant exposure-pathways have limited the successful estimation of toxic impacts in LCIAs. Limited indicators also affect the usefulness of combined assessment particularly those related to life cycle-based risk assessments. Several of the reviewed studies focused on specific case studies, others employed a methodological approach by using frameworks or combined models. Most of these studies did not show actual procedures for integration, and inconsistency in mode of assessment even for those studies employing similar integration approach, presents difficulty in comparing the studies.

Integrating the aspects of LCA and ERA is an ambiguous process, relying on the successful merging of the different aspects of LCA and ERA, including environmental processes and phenomena, mathematical relationships and chemical and environmental data.

There is a need to conceptualise the idea of integrating LCA and ERA, from a generic point of view, to help understand what is required to support the goal of a comprehensive assessment. A more generic framework that links near-field (local scope) and far-field (global scope) fate and exposure related processes, and which can be adapted for assessment of different case studies, is required. A practical guide for practitioners integrating LCA and ERA should be built upon existing information and data, to serve as a starting point in generating a level of uniformity and progress among studies integrating LCA and ERA.

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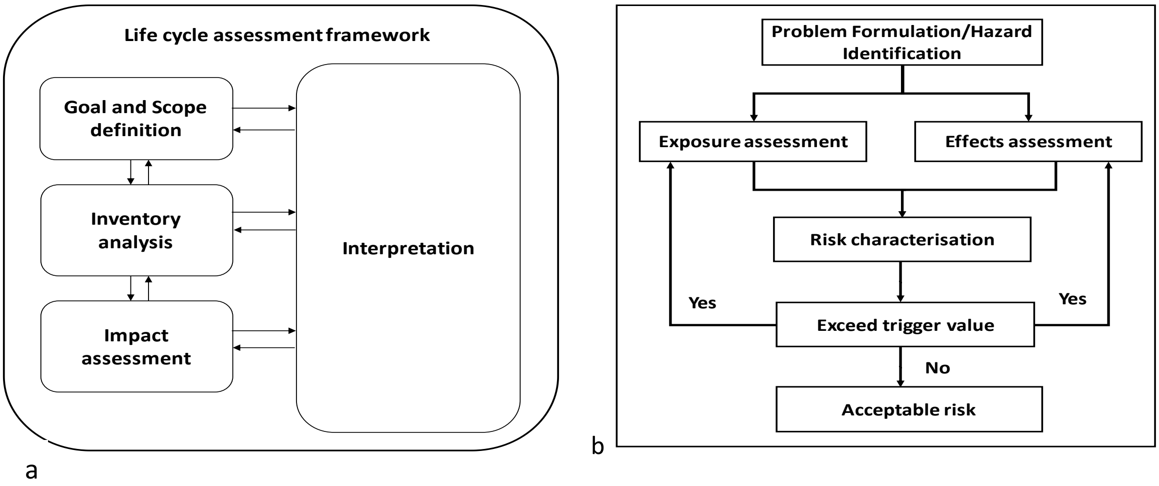

Figure 1: Conventional Frameworks for a) LCA and b) ERA (adapted from (European Union 2010a;Maltby 2006)

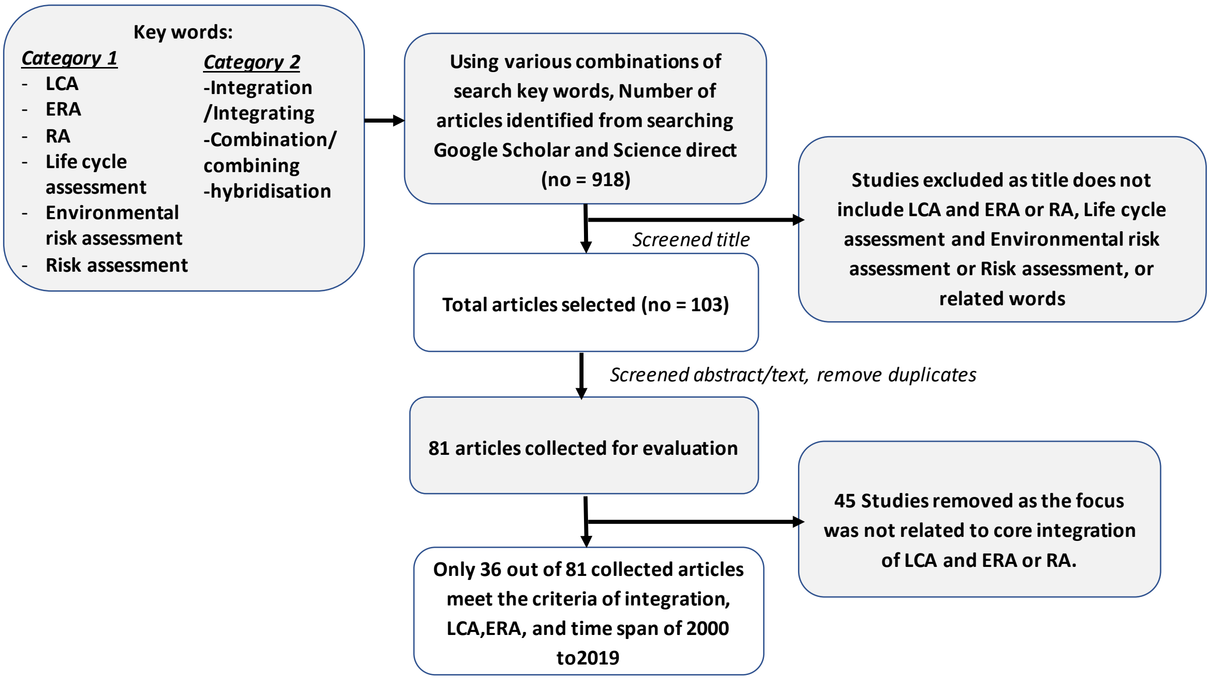

Figure 2: Literature search approach used in the selection of reviewed studies

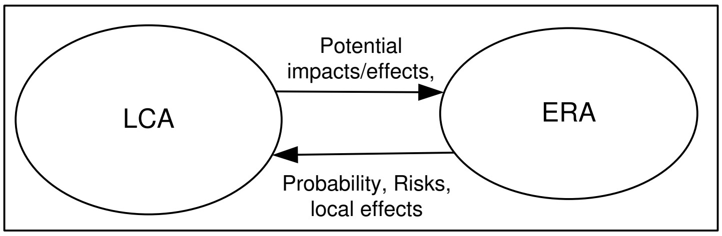

Figure 3: Parallel Integration by combining results of individual assessments

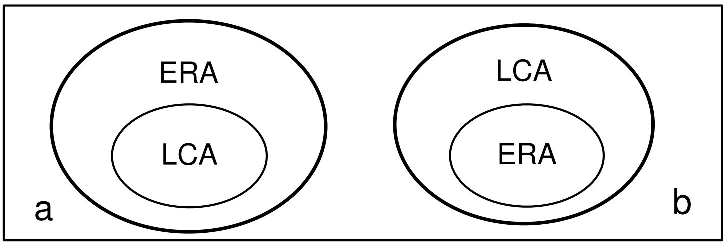

Figure 4: a) Subset Integration by incorporating elements of ERA within LCA framework. b) subset Integration by incorporating LCA elements within ERA analysis

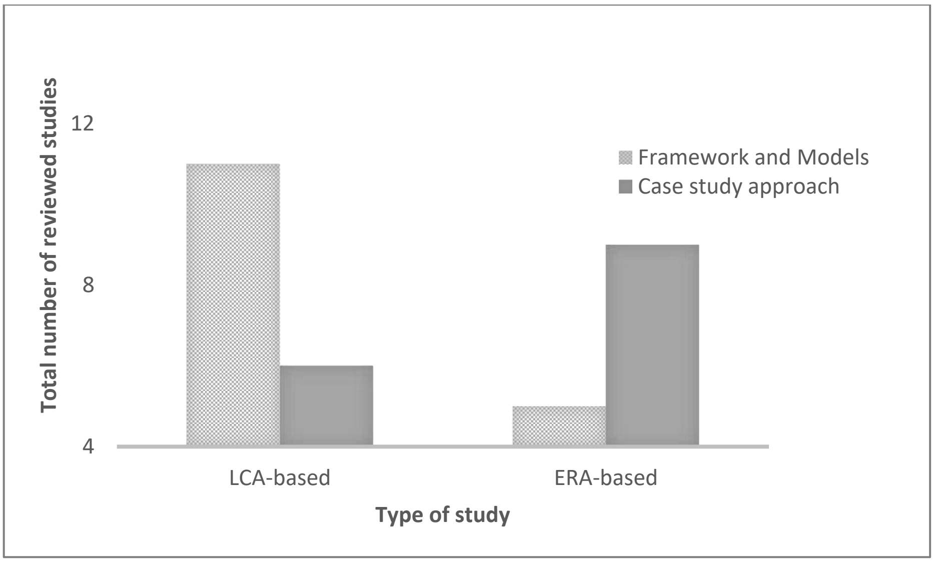

Figure 5: Number of studies that are LCA-based or ERA-based, focusing on either Frameworks/models or Case study approach

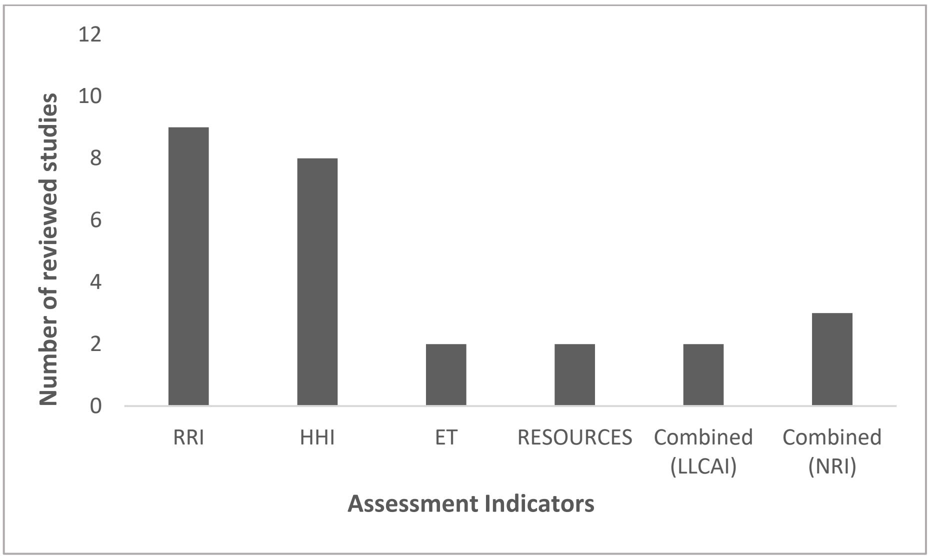

Figure 6: Common Indicators employed by some of the reviewed studies (RRI: Risk related indicators, HHI: Human health impact, ET: Ecotoxicity, LLCAI: Limited LCA Indicators, NRI: No risk indicators included)

Tables

Table 1: Comparison of LCA and ERA [Adapted from (Breedveld 2013) and expanded]

Environmental Assessment	LCA	ERA
Principle	Less is better	Above threshold
Goal	Assessment of potential impacts	Estimation of environmental risks
Scope	Life cycle perspective	Substances released to the environment
Dimensions	Time and space independent	Time and space dependent
Focus	Mass	Concentrations
Approach	Realistic comparisons for product comparison	Worst case for initial risk assessment
Impact assessment	$M = \sum_{s} CF_s * E_s$	$RCR = {}^{PEC}/_{PNEC}$
Common Indicators	*Global Warming Potential; Acidification, ozone depletion, Land use, water consumption, fossil depletion*	Likelihood, Risk quotient (RQ)

***M:** midpoint effect (characterisation step); **s**- substance; **CF**-characterisation factor, **E**-emissions; **RCR**-risk characterisation ratio (effect assessment step); **PEC**-predicted environmental concentration; **PNEC**-predicted no effect concentration*

***Note:** Most LCA studies calculate effects at midpoint (European Union 2010b)*

Table 2: Summary of reviewed studies showing type of study, number of studies in each integration category, and indicators used (for full paper details see Table S1 in the supplementary materials)

Item	**Data from reviewed studies**			
Method of Integration	Parallel	Subset	Others*	Indicator (s) used
LCA-based studies	-	9	11	HH (DALY), HHI, HT, RRI, Energy, GWP, climate change, metal depletion, ΔEF, HQ, CR, CTUe, LCA midpoint (+ toxicity), EQ, OD, FD, PCOF, PMF, IR, EU, AP, ET and land use
ERA-based studies	-	8	6	HQ, Risk (CR), HH, ES, RRI, HHI (carcinogenic & non-carcinogenic), LC50, EC50, EP, PEC, PNEC, climate change, resources, EQ, OD, FD, PCOF, HT, PMF, IR, EU, AP, ET
LCA-ERA based studies	1	-	1	EP, PEC, PNEC and other LCA, economic, and social impacts were considered
Total	1	17	18	

**Others include review studies, complimentary, multi-option and sequential integration methods*

HT: Human toxicity, HHI: Human health impact, RRI: Risk related indicators, ΔEF: Change in Ecological factor, HQ: Hazard quotient, CR: Cancer risk factor, HTTP: Human toxicity potential, EP: Ecotoxicity potential, AP: Acidification potential, EU : Eutrophication, OD: Ozone depletion, FD: Fossil depletion, HH: Human health, EQ: Ecosystem quality, PCOF: Photochemical oxidant formation, IR: Ionising radiation, PMF: Particulate matter formation, PEC: Predicated environmental concentration, PNEC: Predicted no-effect concentration, CTUe: Comparative toxic unit (for freshwater ecosystem), LC50: Median Lethal concentration, EC50: Half maximal effective concentration, GWP: Global warming potential

Table 3: Benefits and limitations of previous LCA and ERA integration methods

Integration Methods	Benefits	Limitations
Parallel	• More comprehensive information related to specific assessment • Reduce complexity of assessments • Outcomes can be systematically analysed using multi-criteria analysis tools	• Time consuming due to requirement for individual data and assessments • Higher cost for parallel assessments • Sometimes conflicting information • Difficulty for policy makers
Subset (LCA in ERA)	• Identification and management of problem shifting between stages of a product's life cycle, and local and global impacts • Quick identification of potential risk reduction areas over life cycle • Opportunity for a more streamlined risk assessment • Reduced cost and time	• Limited indicators • Limited scope (difficult with global impacts) • Risk of double counting
Subset (ERA in LCA)	• Broader scope of impacts considered • Toxicity impacts considered • A more realistic and dynamic assessment is achieved • Reduce time and cost • Help in understanding potential trade-offs and reduce problem shifting	• Some indicators (qualitative) difficult to integrate in LCA • Some aspects of ERA not fully addressed • Difficulty in analysing complex systems (e.g., when multiple processes and products involved in life cycle) • Risk of double counting • Data limitation (e.g., toxicity data to develop relevant characterisation factors)
Others (e.g., complimentary)	• Ease of assessment • Highlights the strength of individual tools • Clearly indicates complimentary benefits	• Does not imply integration • Similar to parallel assessment • Time consuming • High cost

7. Supplementary materials

Table S1:supplementary: Previous studies on LCA and ERA integration

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	**Subset**	**others**				
1	LCA-based	(Flemstrom et al, 2004)	NA	NA	Review	Five types of integration approaches were reviewed including; parallel, subsets, overlap and complimentary methods.	NA	Most common approach of integration of LCA and (E)RA is the Inclusion of eco-toxicological and toxicological parameters in LCIA step of the LCA. e.g., of methodologies: Eco-indicator 99, EPS, EDIP, Impact 2002, USES-LCA.	A holistic approach for chemical management and harmonization of LCA and (E)RA is not yet available. Methodologies differ widely, leading to variable results.
2	ERA-based	(Nishioka et al. 2005)	NA	LCA applied in assessment of local risk	NA	Developed regression models of exposure estimation, and concentration-response functions, for use in building insulation and employed the concept of LCA to evaluate life cycle energy savings.	HHI	Model was used to determine intake fraction for various pollutants from different power sources with population fixed radius. Assessed environmental impacts including energy saving & emissions reduction, risk reduction in morbidity outcome, health benefit.	Limitations on the number of impacts indicators, and too specific to case study, subjective factor in uncertainty analysis.
3	ERA-based	(Shih and Ma 2011)	NA	Life cycle thinking in ERA	NA	Study employed the approach of product life cycle to	HQ, Risk (CR)	Both carcinogenic and non-carcinogenic risks were assessed. Study found that	Fundamental principles of LCA not integrated, and

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	Subset	others				
						evaluate the HH risk of bottom ash utilisation in road pavement construction.		the use phase of paving constructed with bottom ash, presents higher risk to HH, for all the scenarios presented in the study.	global impacts not covered.
4	LCA-based	(Juraske et al. 2009)	NA	Toxicity assessment in LCIA	NA	Study employed LCIA models of toxicity assessment, to evaluate the risk pose by using pesticides in fruit and vegetable plantations.	HH (DALY)	CF's factors for toxicity assessment were derived using fate, exposure and damage factors (Multimedia, multi-pathway exposure models, toxicological data and human health data were utilised). No risk to human health from ingestion of the fruit or vegetables for the specific case study.	Entire life cycle of pesticide not considered (e.g., production), used of average data for damage effects, affects the accuracy factors derived.
5	LCA-based	(Kobayashi et al. 2015)	NA	NA	Review	Assessed 4 different integration methods: 1) Separate LCA & quantitative risk assessment (QRA), 2) LCA as Screening tool; 3) LCA in QRA, & 4) QRA in LCA	NA	The study highlighted key advantages and disadvantages of the different integration methods discussed. So far, no single best approach identified, for all applications. Select integration approach depending on the aim of the study, type of application, availability of data, as well as other constraints of	No specific suggestions given on the way to progress in developing a unified approach of integration.

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	Subset	others				
								projects such as time and cost.	
6	ERA-based	(Liu et al. 2012)	NA	NA	Complimentary approach	Combined ERA, LCA and Criteria based analysis	Resources, HH, ES, RRI	The integrated framework was useful in identifying probabilistic causality of aspect–pathway–receptor–impact relationships and enhances theoretical foundations for impact assessment.	Difficulty in using framework for determination of probabilities of some midpoint effects (e.g., climate change resulting from CO_2 emission). Probabilities of impact were based on subjective judgement, hence limits the complete reliability on results.
7	ERA - based	(Milazzo & Spina, 2015)	NA	LCA as a subset of ERA	NA	Complimentary use of LCA and ERA. Study employed transfer factors applied in RA to calculate impacts on human health.	HHI (carcinogenic & non-carcinogenic	Approach allowed estimation of environmental impacts on a wider scale rather than a site-dimension. Determined the criticalities in some phases of biodiesel production that can cause negative effects on human health and ecosystems.	Problems with the estimation of both the probability of the presence of the individual and the volume of the contaminated compartments, data for this is usually acquired from hazard assessment and

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	Subset	others				
									characterisation step in RA.
8	ERA-based	(Nishioka et al., 2006)	NA	NA	Complimentary use	Extended an existing framework developed for combined input-output LCA and risk assessment for public health impacts from particulate matter, to also address greenhouse gases and the public health consequences of changes in income.	NA*	Model can be used to determine economic impacts associated with particulate matter and greenhouse gas–related midpoints and endpoints	Approach requires some modification to reduce uncertainties
9	LCA-based	(Pizzol et al. 2011)	NA	Toxicity assessment in LCIA	NA	Study analysed and compared different methods for eco-toxicological assessment of 14 metals in LCIA.	NA	Significant variations in different methodologies was highlighted, Eco toxicity factors are much more fragmented compared to human	Significant work is required in this area, to improve assessment factors, even for the most

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	Subset	others				
								toxicity factors. High level of uncertainty is associated with toxicity assessment factors in LCIA.	recommended method (USEtox)
10	ERA - based	(Tobias et al., 2017)	NA	LCA as a subset RA	Complimentary use	Proposed the Integration LCA, RA and human bio-monitoring (HBM), for improved chemical risk assessment.	NA*	Knowledge gap on cumulative exposure and risk assessment of subpopulations for policymaking can be addressed by combining HBM with LCRA (case study of nanomaterials). Approach provided more holistic guide for regulatory and policy making of chemical substances.	Specific to case study: Research is needed in the area of novel biomarkers that are relevant to adverse outcome pathways.
11	LCA-based	(Harder et al. 2015)	NA	NA	Review	Reviewed different studies blending LCA & ERA.	NA	Authors proposed design space for case studies combining LCA & ERA to understand issues/limitations of approach employed in a given case study.	More work is required to develop integration approach that addresses both LCA and ERA perspectives.
12	LCA-based	(Hauschild & Potting, 2006)	NA	NA	Integration of space variations LCIA	Analysis of the integration of spatial differentiation in LCIA and relationship with credibility of	NA	Described the three levels of spatial differentiation (site-generic, site-dependent and site specific) used in impact assessment. Their individual relevance and most accepted. Site-	With increased interest in the use of integrated assessment to support European policies, LCA practitioners need to incorporate

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	Subset	others				
						assessment outcomes.		dependent methods not well accepted by LCA practitioners.	more site-dependent spatial differentiation into LCA CFs.
13	LCA-based	(De Haes et al., 2006)	NA	NA	Review	Described integration of LCA and ERA approaches at three different levels. Analysis of the similarities and differences.	NA	Summarised LCA and ERA relationship on 3 different levels 1) based on theories and mathematical equations, 2) based on overall model structure and 3) based on application. Concluded that the only fundamental difference between LCA and ERA is the use of the functional unit concept in LCA and the use of flows of actual (or absolute) size in (H) ERA.	Combining LCA and ERA at level 2 regarded as impossible due to the fundamental differences in the model structure. Combination at level 3 (application) may be achieve via the use of Toolbox. More work is required to improve integration of both tools at all levels.
14	LCA-based	(Socolof & Geibig, 2006)	NA	Toxicity assessment in LCIA	NA	Used LCA to evaluate the impacts (including human toxicity impact) of leaded and lead-free solders used in the electronics industry.	HT	Findings suggest that a more detailed risk assessment of the process would assist in better understanding of the potential for human health and ecological risks.	A full assessment of the system requires both LCA and ERA*. Case study highlighted that LCA data can be used to identify the need for focused RA.

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	Subset	others				
15	LCA-based	(Paulilo et al. 2018)	NA	Toxicity assessment in LCIA	NA	Focused on evaluating the effect radiological pollutant based on toxicity /risk assessment in LCIA	HHI, Environmental impacts	Suitable methods for use in LCIA stage is lacking. Authors identified two main features as crucial: the ability to treat all types of waste forms by which radionuclides can be released and the use of a fate analysis which returns average (rather than worst case) estimates of impacts.	More research is required to develop novel framework for radiological impact assessment on humans – authors are working on this area.
16	ERA-based	(Grieger et al. 2015)	NA	ERA as a subset of LCA	NA	Focused on evaluating the risk of nanomaterials from a life cycle perspective.	RRI	-Difficult to apply conventional RA for nanomaterials due to complexities and high uncertainty. - Evaluated eight frameworks including Life Cycle- RA against 10 criteria that were considered important for inclusion in nanomaterial risk analysis. -Unique benefits of LCA include “the avoidance of problem shifting” which was considered key for its use as complimentary tool with RA. -Combining RA with LCA can provide more comprehensive risk	There is need for methodological developments in LCA, to enable combined assessment with RA. In addition, the lack of usable physiochemical and (eco) toxicological data and environmental fate and exposure models limits the usability of LCA results.

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	Subset	others				
								management than each assessment could provide separately.	
17	LCA-based	(Galante & Haddad, 2014)	NA	ERA as subset of LCA	NA	Focused on description of LCA and RA as tools for assessing impacts.	NA	Suggested the use of RA as a subset of LCA. Statistical approach (the use of *probi*t equations) to predict the magnitude of exposure, which can be used as input data for LCA.	Approach of integration not available.
18	LCA-based	(Cowell, Fairman & Lofstedt, 2002)	NA	NA	Review	Analysis of both LCA and ERA aspects in relation to decision-making.	NA	Evaluated the similarities and differences of LCA and ERA based on different components of analytical tools. Categories of concern included: philosophical approach of the tools; quantitative versus qualitative assessment; stakeholder participation; the nature of the results; and the usefulness of the results in relation to time and financial resource requirements.	Study did not present specific approach of integration but described the limitations of using individual tools in supporting decision-making.

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	Subset	others				
19	LCA-based	(Linkov et al., 2017)	Multi-criteria decision analysis of output from individual assessment	NA	NA	Parallel approach and Integration of results from individual assessment.	NA	Strategic approach using decision analysis tools e.g., MCDA, to evaluate the trade-offs/compromises between outcomes from individual assessment. Approach suggested in the context of emerging technologies: nanotechnology.	Research is required to develop approach for use of combined LCA and ERA in context of nanotechnology, and in more generic context.
20	LCA-based	(Barberio et al. 2014)	NA	NA	Complimentary approach	Used LCA and ERA as Complimentary tools	RRI, ENERGY, GWP	A step-by-step approach proposed in the use of LCA to evaluate environmental performance of processes under consideration, and the use of ERA to determine the process with the highest risks within the same framework. Potential trade-offs between the two tools were highlighted.	Opportunities for full integration can be explored
21	LCA-based	(Tsang & Sonneman, 2018)	NA	NA	Multi-option approach	Explored the potential use of LCA and ERA to guide development and ensure safety of engineered nanomaterials (ENM) and nanotechnology.	NA*	Developed strategic guidance diagram (SDG) to guide users on when, where and how the individual, combined uses and integrated uses of LCA and RA are required for ENM.	Development of a more integrated and generic approach is still lacking

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	Subset	others				
22	LCA-based	(Herva et al. 2012)	NA	NA	Complimentary approach	Used fuzzy logic to integrate output from individual assessment including ecological footprint.	ΔEF, HQ, CR	Fuzzy Eco-design Index (Factoid) was developed as a measure of sustainability of a product or service. Factoid uses output from individual assessment as input evaluate system sustainability.	Further development of the decision tool is required, to improve the sensitivity to input data, refinement of decision tree. Expand the number of indicators particularly for LCA. Also, Decision tool did not integrate component of individual assessment tools.
23	LCA-based	(Hertwich et al. 2001)	NA	ERA as a subset of LCA	NA	LCA method; CalTOX was employed to determine the human toxicity potential (HTP) of chemical substances in LCI and Toxic Release Inventory.	HTP	Study assessed and calculated HTP values for surface water releases and air emissions of 330 chemical substances. They extended the number of chemicals covered in the HTP and distinguished between cancer and non-cancer effects.	CalTOX was unable to generate HTPs because substantial modifications are required. Expansion of more chemicals is required to broadened assessment scope. Assessment is specific to toxic impact indicators. The influence of chemicals on other

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	Subset	others				
									indicators improve understanding
24	ERA-based	(Benetto et al., 2007)	NA	NA	Complimentary approach	Proposed 3 methods; 1) Generation of new impact results by altering the LCA results through an algorithm using ERA results, 2) substitute LCA results by ERA results, 3) Expand LCA impact categories by defining new impact categories for ERA.	ET,AP,EU	Common impact indicators (for ET) developed from LCA and ERA individual indicators. The combination of LCA and ERA was found to reduce the degree of preference shown by only LCA results.	Study somewhat based on parallel approach as integration was proposed at the results level. Integration only possible with one indicator; ET. Methods for weighting among criteria not presented. Integration is limited to the case of mineral waste reuse/recycling.

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	Subset	others				
25	LCA-based	(Morais & Delerue-Matos, 2010)	NA	NA	Review	Study reviewed LCA of site remediation, and proposed inclusion of regional and local impacts in LCA through integration with RA.	NA	Lack of spatial and temporal differentiation of primary impacts poses a problem for site remediation LCA's. The need for specific primary impact tertiary impacts assessment in the case of site remediation, was highlighted.	Study mentioned potential integration of LCA with RA to address issues of primary impacts assessment in LCA of site remediation. Procedure for integration approach not presentation.
26	LCA-based	(Loiseau et al. 2013)	NA	NA	Adaptation – modified procedures in LCA to adapt to land planning (allow for specific assessment).	A territorial LCA was developed for application in land planning, by modifying the procedure of the conventional LCA. A reference flow approach was proposed instead of the FU.	Global (climate change (HH & EQ), OD, FD, and metal depletion) and non-global impacts (PCOF, HT, PMF, IR, EU, AP, ET and land use	The need for site-specific assessment was recognised in LCA of land planning, was recognised. A territorial LCA focusing on specific geographical territory, was proposed. A set of indicators: a vector grouping a set of land functions was proposed in addition to the potential environmental impacts in standard LCA.	Integration approach specific to case study. The set of indicators representing goods and services for different territory need to be defined, and weighting methods for these indicators need to be evaluated.
27	LCA-ERA	(Chen et al., 2012)	NA	NA	In sequence integration at assessment level	Study utilised specific strengths of individual tools relevant to different stages of the water	EP, PEC, PNEC and other LCA, economic, and social impacts were considered.	Integrated sustainability assessment framework was used to evaluate the sustainability of different wastewater treatment technologies. Limitations of	Integration not achieved at assessment level. Potential approach of tackling issues generated from

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	Subset	others				
						treatment systems, to develop the framework for combined assessment.		individual tools was managed by the proposed combination approach (e.g., risk of recycled water not covered in LCA or MFA, was accounted for, using ERA), while MFA, was used to track and prioritised important substances from inventory.	model differences and boundaries of assessment, was not provided. Development of appropriate weighting criteria for outcomes of assessment is needed, to improve the proposed MCA approach.
28	LCA-based	(Sala & Goralczyk 2013)	NA	ERA* as subset of LCA	NA	Employed the concept of LCT, HERA, and precautionary principles, within the concept of sustainability.	CTUe	Used LCA perspective to assess the intensity of chemical pressure based on characteristics of the release compartment, and further linked the released of chemical and its potential harm for the environment with the carrying capacity of the ecosystem (ecosystem vulnerability), to evaluate the chemical footprint (ChF).	More research is required to develop appropriate relevant indicators, and define new thresholds that describes risks and actual damage to ecosystem health. New methods for identifying and prioritising chemicals for assessment, are needed. Issues with boundaries of assessment and uncertainty also

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	Subset	others				
									need to be addressed.
29	LCA-based	(Breedveld 2013)	NA	ERA as a subset of LCA	NA	Employed the ERA concept and models onto the wider boundary of LCA: LCBRA.	NA*	The combined application of RA and LCA to emerging risks (iNTeg-Risk project) highlighted several benefits; new safety Paradigm, and introducing radical change in health and safety management etc.	Procedure for integration not shown in the study. Relevant indicators need to be shown.
30	ERA-based	(Pivato et al. 2016)	NA	NA	Study focused on development of toxicity data for use in ERA and LCA	"matrix-based" approach employed instead of substance-based approach in toxicity assessment of pollutants.	LC50, EC50	Study developed new effect factors for potential use in the derivation of CF's for toxicity Impacts in LCA.	Study did not present actual integration of the LCA and ERA. Toxicity data (effect factor: EF) developed are interim, hence further research required to reduce uncertainty and increase usefulness of the factors.

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	Subset	others				
31	ERA-based	(Aramaki et al., 2006)	NA	NA	Complimentary approach	RA and LCA frameworks were used in complimentary manner, to assess HH risk associated with urban wastewater system. RA model was used to estimate the reduction in disease burden while LCA approach was applied to estimate the environmental loading affecting human health	DALY	Study found potential trade-offs between outcome of RA and LCA. Increased risk To HH due to environmental loading was found, as a result of construction of wastewater systems to reduce local health risks.	Presented approach and case study is underpowered by limited data. Exposure-pathways not evaluated in assessment, and limited scope of the LCA aspect was used. More relevant indicators required.
32	ERA-based	(Matthews et al., 2002)	NA	LCA as a subset of ERA	NA	Study proposed 5 approaches of integrating LCA and ERA. First approach employed output from EIO-LCA, to determine risk to human health in a given population. Remaining approaches include site-dependent and	NA*	Presented several approaches for translating life cycle inventory data into changes in ambient air quality, which can be used to determine changes in health effects through RA.	Actual methodologies not shown in the study. Apart from the first approach, LCA perspective not very clear in the remaining approaches. More work is needed to develop robust methods of

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	Subset	others				
						site specific related approaches.			inventory analysis, and integration methods.
33	LCA-based	(Bare 2006)	NA	Toxicity assessment in LCIA	NA	Study employed both RA and the LCIA method TRACI, to assess HH carcinogenic and non-carcinogenic emissions.	LCA midpoint (+ toxicity) indicators and RRI	Significant differences between LCIA human health and RA human health were presented. The complimentary roles of the two tools; USEPA's TRACI (for LCA) and RSEI (RA), was analysed within an integrated assessment.	Integration was based on separate assessment with TRACI and RSEI (as in parallel approach). Study did not show actual integration methods.
34	ERA-based	(Kuczenski et al., 2011)	NA	Life cycle thinking in ERA (life cycle aware" RA)	NA	Proposed the incorporation of process flow model of LCA into the ~~risk~~ RA. Modelled toxic flows in the life cycle of a child's toy containing dibutyl phthalate (DBP) using risk and toxicity data.	Risk related Indicators	The use of LCA approach on toxic chemical use, enables the development of safer alternatives while informing analysts of potential trade-offs and unforeseen consequences of alternative designs.	Limited indicators, approach narrows the scope of LCA to impact assessment alone, and also ignores some aspects of the individual tools.

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	Subset	others				
35	ERA-based	(Harder et al. 2014)	NA	RA(QMRA) integrated into the LCA framework	NA	Site specific pathogen RA was employed in estimating the burden of disease, in the context of municipal wastewater and sewage sludge management.	DALY	Set of exposure pathways were generated using past literature studies and model approach, to estimate risk of pathogen to human health. Study proposed the inclusion of QMRA in LCIA methodologies, in such a way that risk estimates are closely related to those present in LCIA models, with less site-specificity and less exposure pathways.	Study did not present integration methods. The proposed approach may be associated with high uncertainty, and perhaps reduce accuracy in the context of pathogen related RA.
36	LCA-based	(Hedberg et al. 2019)	NA	Toxicity assessment in LCA	NA	Study focused on development of CFs for calculation of toxic impacts of metals (chromium (Cr) and nickel (Ni)) in LCIA, focusing on site-dependent regional water chemistry (EU). Equilibrium modelling as well as DGT measurements were used to estimate the	NA	Presented the influence of physiochemical changes of some metals in freshwater compartment, on the values of their CFs, and resulting toxic impacts. Generated new FFs, EFs, and CFs for Ni, Cr (III), and Cr (VI) in the model freshwater and compared with default USEtox. Site-dependent regional focus improved accuracy of LCIA.	Study did not show procedure for integrating LCA and ERA as it was case study focused. Model is limited to regional context, and specific substance (metals considered).

S/NO	Type of study	Reference	Method of Integration			Approach used for Integration	Indicator (s)	Findings/Highlights	Research Gaps and limitations of integration methods
			Parallel	Subset	others				
						bioavailable metal fraction.			

NA: Not applicable; NA*: Not available from the reviewed study, HT: Human toxicity, HHI: Human health impact, RRI: Risk related indicators, ΔEF: Change in Ecological factor, HQ: Hazard quotient, CR: Cancer risk factor, HTTP: Human toxicity potential, EP: Ecotoxicity potential, AP: Acidification potential, EU : Eutrophication, OD: Ozone depletion, FD: Fossil depletion, HH: Human health, EQ: Ecosystem quality, PCOF: Photochemical oxidant formation, IR: Ionising radiation, PMF: Particulate matter formation, PEC: Predicated environmental concentration, PNEC: Predicted no-effect concentration, CTUe: Comparative toxic unit (for freshwater ecosystem), LC50: Median Lethal concentration, EC50: Half maximal effective concentration, GWP: Global warming potential, ERA*: Ecological risk assessment, LCT: Life cycle thinking, HERA*: Human and ecological risk assessment, QMRA: Quantitative microbial risk assessment, FFs: Fate factor, EFs: Effect Factors, CFs: Characterisation factors, DGT: diffusive gradient in thin-films