Revisiting the challenges of ozone depletion in Life Cycle Assessment

Anne van den Oever[1], Stefano Puricelli[2], Daniele Costa[3], Nils Thonemann[4], Maeva Lavigne Philippot[1], Maarten Messagie[1]

1 Vrije Universiteit Brussel
2 Politecnico di Milano
3 VITO (Vlaamse Instelling voor Technologisch Onderzoek)
4 Leiden University

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Abstract

Recent work has highlighted the interconnected impacts of stratospheric ozone depletion, ultraviolet (UV) radiation, and climate change across various sectors, including water quality, agriculture, human health, and biodiversity. Increased UV-B exposure has diverse environmental impacts, including potential benefits like enhanced plant resistance and reduced vitamin D deficiency. However, quantification of these effects remains incomplete. Life Cycle Assessment (LCA) serves to quantify environmental impacts of product systems. This review revisits challenges the related to ozone depletion in LCA. It is shown that the currently available LCA ozone depletion practices are unsuitable for supporting decision-making. The combined effects of outdated background databases and incomplete impact assessment methods must be further investigated. Collaboration with atmospheric scientists and expansion of substances covered by characterization models are required. The study emphasizes the need to address interlinkages between impact categories and recommends climate scenario-dependent characterization for robust decision-making in an uncertain world.

Anne E.M. van den Oever[1,*], **Stefano Puricelli**[2], **Daniele Costa**[3], **Nils Thonemann**[4], **Maeva Lavigne Philippot**[1], **Maarten Messagie**[1]

[1] *Electric, Vehicle and Energy Research Group (EVERGi), Mobility, Logistics and Automotive Research Centre (MOBI), Department of Electric Engineering and Energy Technology (ETEC), Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium*

[2] *AWARE - Assessment on WAste and REsources, Department of Civil and Environmental Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133, Milano, Italy*

[3] *VITO/EnergyVille, Boeretang 200, 2400 Mol, Belgium*

[4] *Institute of Environmental Sciences (CML), Leiden University, 2300 RA Leiden, The Netherlands.*

[*]**Corresponding author:** anne.van.den.oever@vub.be

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1. Introduction

The ozone layer in the stratospheric region of the atmosphere plays a pivotal role in protecting living species on Earth. It filters part of the ultraviolet (UV) radiation from the sun, performing a silent but fundamental task. The UV radiation increases the risk of, among others, skin and eye damages in humans and animals, and reduces photosynthesis in plants (FOEN, 2021; Hauschild et al., 2018). The crucial role of stratospheric ozone has been endangered by the gradual increase in anthropogenic emissions of ozone-depleting substances (ODSs). These substances can be found in various sources such as automobile and truck air conditioning units, domestic and commercial refrigeration and air conditioning/heat pump equipment, aerosol products, portable fire extinguishers, insulation boards, panels, pipe covers, and pre-polymers (UNEP, 2020a)

The awareness of the threat to the ozone layer was raised in 1974 when Molina & Rowland (Molina and Rowland, 1973) suggested that two chlorofluorocarbons (CFCs) could function as catalysts for ozone destruction in the stratosphere. However, it was not till the mid-1980s, when scientists discovered the ozone hole over Antarctica, that the issue gained large-scale attention (Drake, 1995). Consequently, the Vienna Convention for the Protection of the Ozone Layer was established (Solomon et al., 2020), with the objective of promoting global cooperation in limiting the anthropogenic contribution to ozone layer depletion (UNEP, 2020b). Building upon the Vienna Convention, the Montreal Protocol on Substances that Deplete the Ozone Layer, commonly known as the Montreal Protocol (MP), entered into force in 1989 (Singh and Bhargawa, 2019). Initially, the MP regulated five CFCs and three halons, but, thanks to subsequent amendments, today, it governs the production and consumption of nearly 100 ODSs.

Thanks to this global effort, a decline in ODS emissions has been observed since the late 1980s (Fang et al., 2019). The atmospheric abundances of most ODSs are also decreasing after reaching their peak in the 1990s and 2000s (Fang et al., 2019). More importantly, a recovery of the ozone layer has been observed (Singh and Bhargawa, 2019), averting the negative effects of UV exposure (Barnes et al., 2019). Many researchers have predicted a complete recovery of the ozone column to 1960 levels, but the timing of this recovery remains uncertain. Some estimate a recovery before the middle of this century, while others suggest that full recovery may not occur before 2100 (Singh and Bhargawa, 2019).

Recent scientific literature has highlighted that the quantification of the environmental effects and benefits of ozone layer depletion is currently lacking (Barnes et al., 2019). Also, challenges to full recovery subsist, and additional measures are required (Fang et al., 2019; Portmann et al., 2012; Solomon et al., 2020). Therefore, continuous monitoring of ozone depletion threats and fostering close collaboration between scientific findings and policy decisions remain imperative

(Portmann et al., 2012).

Life Cycle Assessment (LCA) is a technique for quantifying the potential environmental impacts of a product system, and it has various applications, including “informing decision-makers in industry, government, or non-government organizations for strategic planning, priority setting, product or process design or redesign” (ISO, 2006). LCA can be a valuable tool to support decision-making for ozone layer protection measures. The inclusion of the ozone depletion impact category in life cycle impact assessment methods (LCIA) dates back to the early 1990s when ozone depletion potentials (ODPs) for halogenated hydrocarbons (WMO, 2022) were used to develop characterization factors (CFs) of the CML impact assessment method (Heijungs and Guinée, 1992). Already then, several challenges and limitations of the ozone depletion impact assessment method were mentioned, such as the complex interactions between carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone depletion, and the lack of ODPs for substances emitted by planes, e.g., nitric oxide (NO) (Heijungs and Guinée, 1992). At the time, scientific understanding of these issues was not advanced enough to calculate robust ODP values for non-halogenated hydrocarbons (Heijungs and Guinée, 1992). Lane and Lant (2012) reviewed the literature on the atmospheric science of ozone depletion and concluded that the inclusion of ODPs for N_2O in LCIA methods was recommendable and that the state of modelling was mature enough to do this. Hauschild et al. (2013) reviewed LCIA methods, and, despite the existing limitations, the ozone depletion impact category at midpoint received the highest quality classification, “recommended and satisfactory”, mainly because international agreements exist. The same study judged the endpoint characterization model from Struijs et al. (2010) as the best existing at the time. Now, 10 years later, we revisit the challenges related to ozone depletion in LCA through this scoping review aiming to answer the following research questions:

I. Is the current practice of LCA for ozone layer depletion suitable for decision-making support?
II. If not, which improvements can be suggested to address these challenges?

2. Methodology

The review process was conducted in two steps. Initially, a comprehensive analysis of contemporary approaches within LCIA methods was carried out to understand how the quantification of ozone depletion is currently addressed. The selection of pertinent LCIA methods was based on their inclusion in the widely used platforms SimaPro 9.5 and Gabi 10.7. Methods that were marked as superseded, or that were exact duplicates of other LCIA methods were excluded. For each LCIA method, the most recent documentation was retrieved. Thorough investigation was then undertaken for each selected LCIA method, involving a systematic examination of primary data sources, CFs, and underlying model assumptions.

The subsequent review phase aimed to gain an understanding of the state-of-art of ozone depletion science and policy. Notably, the most recent authoritative assessment of ozone depletion (WMO, 2022) was reviewed. This report, generated quadrennially by the collaboration between the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) serves to apprise stakeholders under the MP of the prevailing status and developments in ozone depletion. Additionally, two searches were performed in the Scopus, Web of Science, ScienceDirect and PubMed databases. The first search query aimed at identifying recent (published post-2017) reviews on the topic of ozone depletion, while the second search aimed at finding recent scientific articles and reports on environmental policy related to ozone depletion.

Following the exclusion of duplicates, 317 articles and reports where screened based on abstracts and a collection of 26 articles and reports were selected as they provided valuable insights related to the research questions. The systematic evaluation of the identified literature on ozone depletion science was out of the scope of the review. Rather, the insights extracted from these articles and reports were used to support the analysis of the modelling of ozone depletion in LCA, following the structure of the LCA phases as defined by (ISO, 2006). The full details of the review protocol are provided in Appendix A, while the corpus of reviewed literature is available in the Appendix B.

3. Ozone-depleting substances: catalysts and climate interplay

Before delving into the various mechanisms responsible for ozone layer depletion, it is important to understand the key terms and the normal equilibrium between ozone formation and destruction (Figure 1). The Chapman mechanism, describing this normal equilibrium cycle, is what causes the ozone layer to exist. The thickness of this layer is measured in Dobson Units (DU), representing the thickness that a pure ozone layer would have under standard conditions (atmospheric pressure and 0° C). A normal thickness is 290 DU, equal to a 3-mm layer, while the thickness can be considered critically low when it falls below 220 DU (Hauschild et al., 2018). This level is only transgressed over Antarctica during Austral Spring (Steffen et al., 2015), leading to the ozone hole.

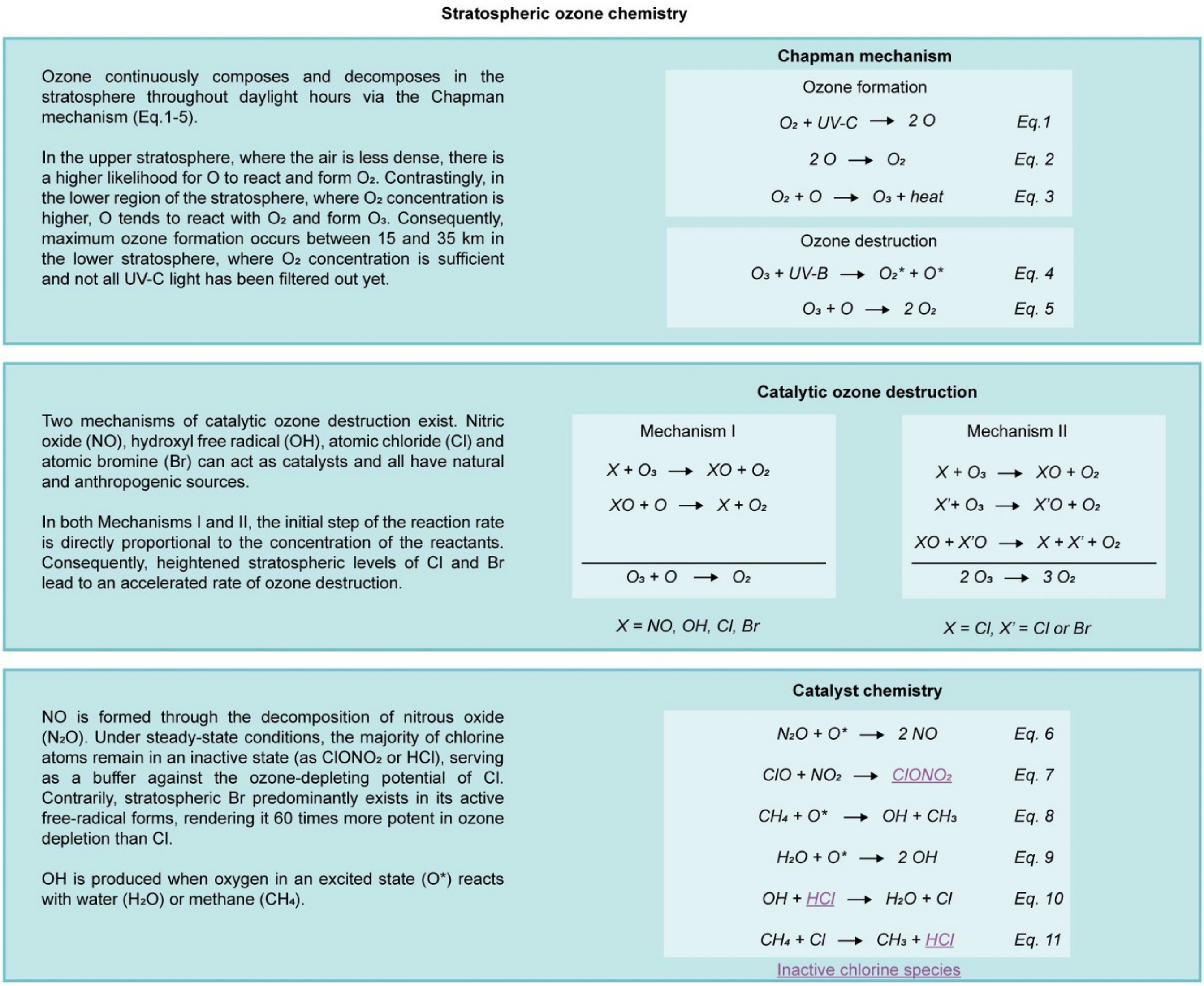

Figure 1. Summary of stratospheric ozone chemistry following the explanation in (Baird and Cann, 2012a, 2012b).

Diverse interpretations of ODS have been put forth. In theory, any substance that leads to increased stratospheric concentrations of ozone destruction catalysts (NO, OH, Cl, or Br) is an ODS. Within the MP, only volatile compounds containing Cl and/or Br, subject to regulation under the Protocol, are classified as ODSs (UNEP, 2020a). This subset of ODSs will be referred to as “controlled ODSs”. These specific ODSs emanate from various sources (FOEN, 2021): I) diffuse emissions from foam insulation materials containing ODSs already in buildings and refrigeration systems; II) losses from refrigeration and air conditioning systems and heat pumps; III) emissions from the disposal of equipment containing ODSs; IV) halon emissions from fire control equipment and systems. Emissions of controlled ODSs have historically been the primary culprits behind ozone layer depletion and the formation of the "ozone hole" (WMO, 2022). The annual occurrence of the ozone hole is influenced by unique Antarctic weather conditions, prompting the conversion of inactive chlorine into its reactive form, causing massive ozone depletion (Baird and Cann, 2012b).

It is worth mentioning that certain controlled substances, such as CH_3Cl and CH_3Br, also possess natural origins, primarily originating from the ocean (Cadoux et al., 2022). Furthermore, specific chlorine and bromine-containing compounds with extended lifetimes, like halothane, are not yet controlled by the MP (WMO, 2022). All long-lived organic ODSs with lifetimes > 0.5 years, irrespective of their controlled status or natural origins, will be collectively referred to as "traditional ODSs".

Due to the extended atmospheric lifetimes of most traditional ODSs, their concentrations in the stratosphere have remained relatively stable over the past two decades (Figure 2) (Vuppaladadiyam et al., 2022). Only shorter-lived chemicals, such as methyl chloroform with a 5-year lifetime, have been depleted from the stratosphere. The consistent trends observed in stratospheric ODS measurements indicate that ODS emissions have been declining, as continuous releases would have led to a build-up of ODSs in the stratosphere.

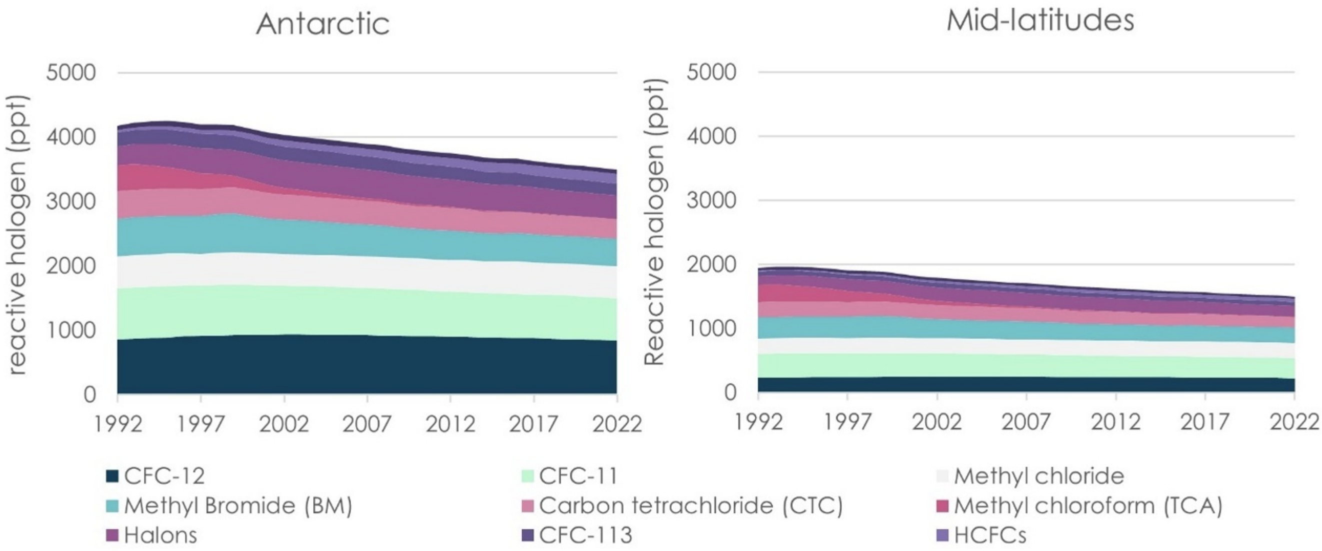

Figure 2. Stratospheric abundances of long-lived ozone-depleting substances (ODS) in the Antarctic and mid-latitudes in ppt based on NOAA measurements. CFC = chlorofluorocarbons. Halons represent Halon 1211, Halon 1301, and Halon 2402, all controlled by the MP. WMO minor represents CFC-114, CFC-115, Halon 2402, and Halon 1201. Adapted from (GML, 2023).

Another class of ODSs comprises the halogenated very short-lived substances (VSLSs) with atmospheric lifetimes of less than 0.5 years and which may stem from either anthropogenic or natural sources (WMO, 2022). A large fraction of VSLSs is destroyed in the troposphere, and the actual effect on the stratosphere depends on emission location, troposphere-stratosphere transport patterns, chemical processing, and deposition processes (WMO, 2022). Despite their short lifetimes, they can still contribute to ozone depletion, particularly when emitted in regions with swift transport or directly into the stratosphere, for example, through the exhaust from rockets employing solid propellants (Dallas et al., 2020). Emissions of chlorinated VSLSs used as solvents or chemical feedstocks have been increasing since the late 2000s and may continue to grow (Chipperfield et al., 2020). Currently, VSLSs are not subject to regulation under the MP (Chipperfield et al., 2020).

A third type of ODSs are NOx, H_2, H_2O, OH, and HCl, henceforward called inorganic ODSs. H_2 can be converted to H_2O, which can be converted to OH. OH, NOx, and HCl act as ozone destruction catalysts in Mechanism I. These substances are not usually considered ODSs, since they have too short lifetimes to reach the stratosphere. However, they may be emitted directly to the stratosphere from rocket or supersonic aircraft exhaust, thus impacting the ozone layer (Brown et al., 2023). Currently, this group of ODSs is not controlled under the MP.

A fourth type of ODSs are stratospheric aerosols. For instance, aluminium and soot particles emitted from rocket exhausts and reflective aerosols from volcanic eruptions or proposed stratospheric aerosol geoengineering endeavours act as catalysts for ozone destruction (Dallas et al., 2020; Kravitz and MacMartin, 2020). At the surface of these aerosols, the inactive chlorine species can react quicker, increasing the concentration of ozone destruction catalysts (Brown et al., 2023; Ross and Vedda, 2018). With the current growth trends in the global space sector, rocket launches could increase significantly in the coming decades, leading to ozone depletion impacts comparable to or even surpassing the effects of all banned ODSs combined (Miraux, 2022).

Lastly, there exist substances with indirect impacts on ozone depletion. Greenhouse gases (GHGs) such as CO_2, N_2O, and CH_4 also exert an indirect influence by cooling the stratosphere through solar radiation reflection, thus modifying ozone destruction kinetics (Fang et al., 2019). The reaction rates of Mechanisms I and II rely on the stratospheric temperature, which is lowered by heightened stratospheric GHG concentrations (Baird and Cann, 2012a). Moreover, N_2O and CH_4 produce NOx and OH, respectively N_2O and CH_4, both of which act as catalysts for ozone destruction. Furthermore, both NOx and methane additionally influence the conversion of reactive chlorine to its inactive state (Baird and Cann, 2012b).

Beyond stratospheric cooling, GHGs also contribute to climate change, which has multifaceted interactions with the ozone layer. Notably, global warming increases the release of natural ODSs from the ocean to the atmosphere (Cadoux et al., 2022; Fang et al., 2019). Climate change also affects atmospheric circulation patterns, which cause changes in ozone, water vapor, and ODS distributions (Garcia, 2021; Tian et al., 2023). Both stratospheric ozone depletion and climate change may also increase tropospheric ozone formation as higher amounts of UV-B reaching the troposphere will strengthen the photochemical ozone production processes (Barnes et al., 2019) and the stratosphere-to-troposphere circulation patterns (Bernhard et al., 2020; Garcia, 2021). These interlinkages are a part of the complex coupling between climate change and ozone depletion (Figure 3), and continuous monitoring and improved modelling are required to understand these links better. It is worth noting that despite representing the largest contribution to stratospheric ozone destruction today (Fang et al., 2019), N_2O is not controlled by the Montreal Protocol (WMO, 2022).

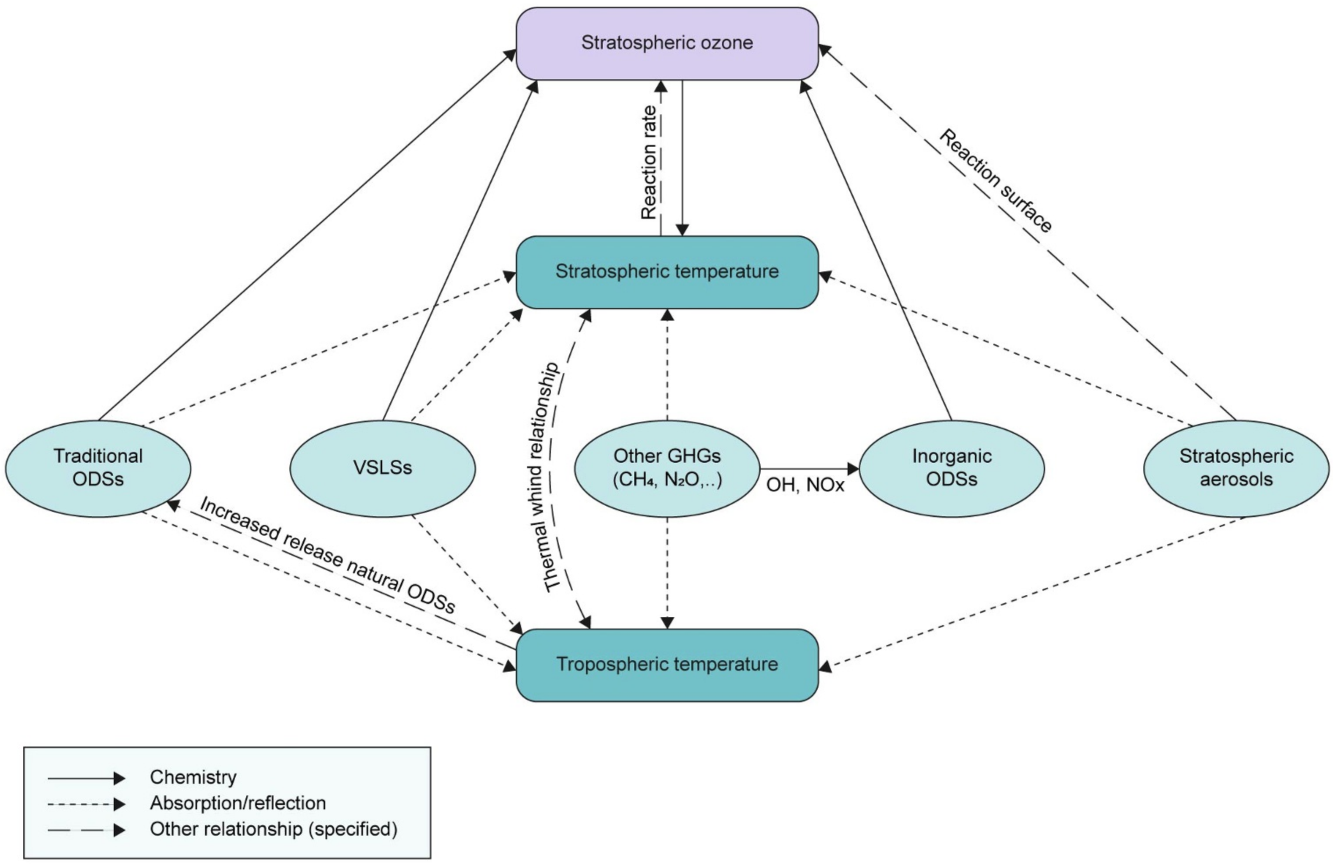

Figure 3. Different interactions between ozone-depleting substances (ODSs), LCV gases (GHGs), stratospheric ozone, and temperature. Other GHGs refer to any GHG that are not included in the groups “Traditional ODSs” or “VSLSs”. Adapted from (WMO, 2011).

4. Ozone depletion in LCA

The LCA framework comprises four interconnected phases (Figure 4). Each step in the LCA process builds upon the previous ones, and it is crucial to consider all phases simultaneously to ensure a meaningful impact assessment.

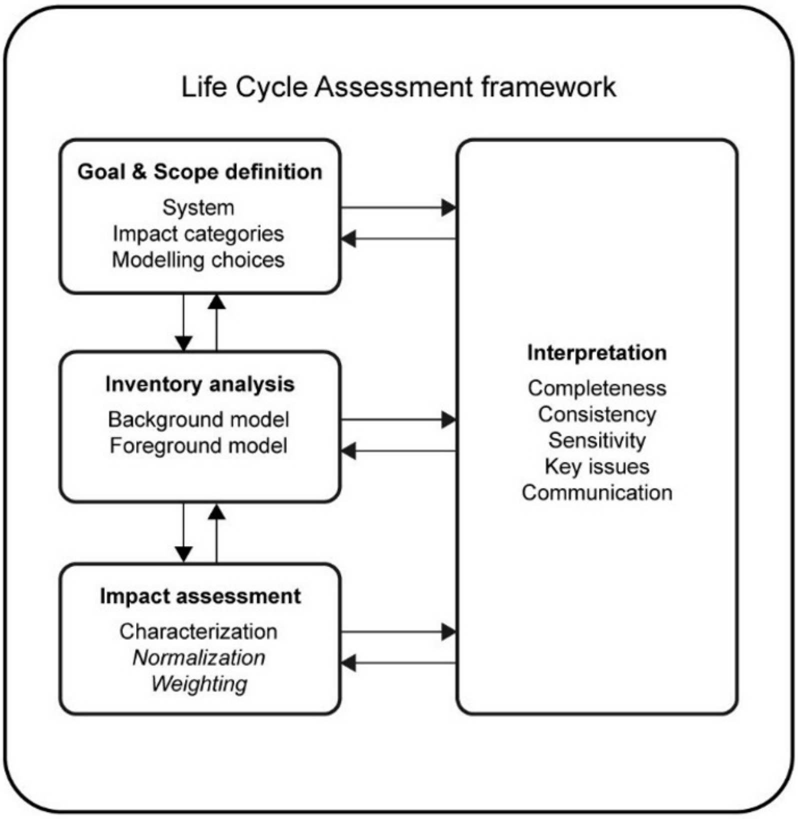

Figure 4. The four phases of the Life Cycle Assessment Framework and their relationships. Normalization and weighting are optional. Adapted from (ISO, 2006; Laurent et al., 2020).

4.1. Goal and scope

Starting with the goal and scope phase, the relevance of ozone depletion as an impact category has been questioned. If ozone depletion is no longer a significant concern, there might be no need to include it in LCA studies, and efforts to improve existing methods may not be justified. Some argue that the ozone layer is recovering, and the health impacts from historical damage are expected to decrease in the future. This perspective is supported by LCA experts who ranked ozone depletion as the second-least important impact category for human health in EF 3.1 (Sala and Cerutti, 2018). Furthermore, a global "LCA of the world" based on the year 2000 inventory of anthropogenic emissions and extractions using IMPACT World+ demonstrated a negligible contribution of ozone depletion to total human health damage (Bulle et al., 2019). However, considering the identified limitations in characterization discussed in section 3.3.1, the reliability of these results must be questioned. Additionally, others contend that ozone depletion remains relevant in LCA, given the goal of assessing a wide range of potential impacts (Lane and Lant, 2012). Additionally, the emergence of new potential threats to the ozone layer, such as large-scale deployment of new technologies, must be considered. For example, ozone depletion remains an important impact category for the space sector. Additionally, model simulations demonstrate that large-scale deployment of geoengineering projects, such as injecting sulphate aerosols into the stratosphere, could significantly impact stratospheric ozone chemistry and transport mechanisms (Kravitz and MacMartin, 2020; WMO, 2022).

Similarly, it remains an important impact category for the agricultural sector, due to fertilizer-related N_2O emissions. Furthermore, ozone depletion is relevant for the chemical industry, as data gaps between ODS consumption reports and atmospheric measurements point to potential leakage issues from ODS serving as precursors or intermediates (Andersen et al., 2021; Vollmer et al., 2020; WMO, 2022). Finally, even if the likelihood of critically depleting the ozone layer is currently low, the consequences related to its depletion affect all life forms on Earth. Given this risk, it is the author's perspective that it is appropriate to continue maintaining and improving the ozone depletion impact assessment.

4.2. Life cycle inventory

Another crucial aspect of conducting a meaningful impact assessment is using a relevant life cycle inventory. Previous studies have revealed that for construction products (Silva et al., 2020) and heavy-duty transport (van den Oever et al., 2023), the predominant contribution to ozone depletion originates from background processes. Therefore, the accuracy of background databases is pivotal in achieving reliable ozone depletion impact assessments, except in cases where product systems incorporate refrigerants with high ODP in their foreground model. However, conventional LCA databases have been found lacking in representing the phase-out of ODSs mandated by the MP (Puricelli et al., 2022; Roibás et al., 2018; van den Oever et al., 2023). For example, Roibás et al. (2018) found that generic pesticide datasets in the United States environmentally-extended input-output (USEEIO) database (Yang et al., 2017) contain Halon 1001, whereas the import and production of this substance have been banned in developed countries since 2005. They also found that using the ecoinvent v3.1 database (Wernet et al., 2016), the biggest impacts were linked to fugitive emissions of halon 1211 and halon 1301 from fire extinguishers and cooling systems (present in crude oil production and natural gas production installations). Puricelli et al. (2022) made the same observation in their LCA of passenger cars. Imports and production of both halons have been banned in all countries since 2010 (UNEP, 2020a). Although existing installations are still allowed to recycle halon 1211 and halon 1301, it can be expected that the stocks will steadily decrease in the coming years. This limitation implies that utilizing such databases for ozone depletion impact assessment may lead to significant overestimations of the ODP associated with banned substances (Bueno et al., 2016; Hauschild et al., 2018; Senán-Salinas et al., 2022). The implications of these overestimations are particularly concerning for prospective studies, as the usage of banned substances is projected to decrease over time. Hence, it becomes imperative to address this issue by updating background databases, such as the ecoinvent database, to ensure a comprehensive reflection of both global regulations (such as the MP) and regional legislations (e.g., the Ozone Regulation in the European Union) (Senán-Salinas et al., 2022). On the other hand, qualitative estimates on ODS leakages from existing installations and insulating foams are lacking (Solomon et al., 2020) and must be added to existing LCI databases. Only through such updates can accurate and reliable assessments of ozone depletion impact be assured, facilitating informed decision-making and effective policy implementation. The substitution of ODSs will also affect the climate change results and even other impact categories. For example, hydrofluoroolefins (HFOs) are gradually replacing CFCs. However, certain HFOs are converted to trifluoroacetic acid in the atmosphere, which is a toxic substance (WMO, 2022).

Regarding the foreground model, ensuring the availability of all relevant emissions is crucial. The challenges associated with this phase are case-specific, but some illustrative examples of risks can be provided. For instance, ongoing investigations into new rocket and aviation propellants are noteworthy, but their exhaust emissions are often absent from environmental assessments due to a lack of in-situ exhaust measurements (Brown et al., 2023; Dallas et al., 2020). For agricultural processes, accurate N_2O emission inventory data is a bottleneck (Lane and Lant, 2012; Portmann et al., 2012). To enhance the foreground models of chemicals, it becomes essential to quantify ODS leakages accurately. While the present atmospheric ODS monitoring tools possess sufficient analytical power for such assessments, it is imperative to broaden the observation network's geographic coverage (Fang et al., 2019) and undertake more systematic investigations into monitoring "unanticipated emissions" stemming from chemical intermediates, as emphasized by recent research (Fang et al., 2019; Vollmer et al., 2020).

4.3. Life Cycle Impact Assessment

4.3.1. Characterization

During the LCIA stage, CFs are applied to a life cycle inventory result in order to obtain the common unit of the impact category indicator. These CFs are categorized into two distinct types: midpoint and endpoint. In the case of endpoint categories, the characterization model encompasses the entirety of the cause-effect chain, starting from emissions and culminating in impacts on so-called endpoints or areas of protection (AoP), and the results are articulated in units such as disability-adjusted life years (DALYs) for the AoP human health or analogous metrics. Conversely, midpoint categories represent a state somewhere along the cause-effect chain (Hauschild et al., 2018). In the case of ozone depletion, the midpoint characterization factor of an ODS is quantified through the ODP, a measure of its efficacy in depleting the ozone layer. The ODPs periodically published by the WMO are internationally accepted and used in LCIA methods. These ODPs refer to a system in a steady state, describing the time-integrated impact over an infinite time horizon, i.e. the ozone depletion during the entire life of substances is accounted for (Verones et al., 2020). The general concept of an ODP is explained by the following equation (Guinée et al., 2002; Hauschild et al., 2018; WMO, 2022):

$$ODP_i = \frac{\Delta\left[O_3\right]_i}{\Delta\left[O_3\right]_{CFC-11}} \qquad \text{Eq. 12}$$

The numerator in Eq. 9 represents the change in global ozone concentration due to the emission of a given mass of a substance *i,* and the denominator represents the respective change due to the same mass emission of CFC-11. The ODP is set at 1 for CFC-11 and, for the other ODSs, is measured in kg CFC-11 eq/kg.

The ODPs reported in the last WMO assessment (WMO, 2022) were obtained from atmospheric model simulations or by using a semi-empirical relationship, e.g., the one reported in (Papanastasiou et al., 2018):

$$ODP_i = \frac{n_{Cl}}{3} \times \frac{f_i}{f_{CFC-11}} \times \frac{\tau_i}{\tau_{CFC-11}} \times \frac{m_{CFC-11}}{m_i} \qquad \text{Eq. 13}$$

where n_{Cl} is the number of Cl atoms in the molecule, 3 is the number of Cl atoms in CFC-11, f is the fractional release factor (dimensionless), τ the global atmospheric lifetime in years, and *m is* the molecular weight in g/mole. For brominated and iodine molecules, the number of atoms is multiplied by 60 and ~250, respectively. Notably, when current atmospheric conditions are used in atmospheric model simulations, they yield results that are in agreement with those obtained from semi-empirical methods (WMO, 2014).

When reviewing the characterization models of currently relevant LCIA methods (Figure 5), it becomes clear that they differ in the time horizon, the CF data sources, the number of substances included in the characterization model, their consideration of midpoint and/or endpoint categories, and the encompassed endpoint effects.

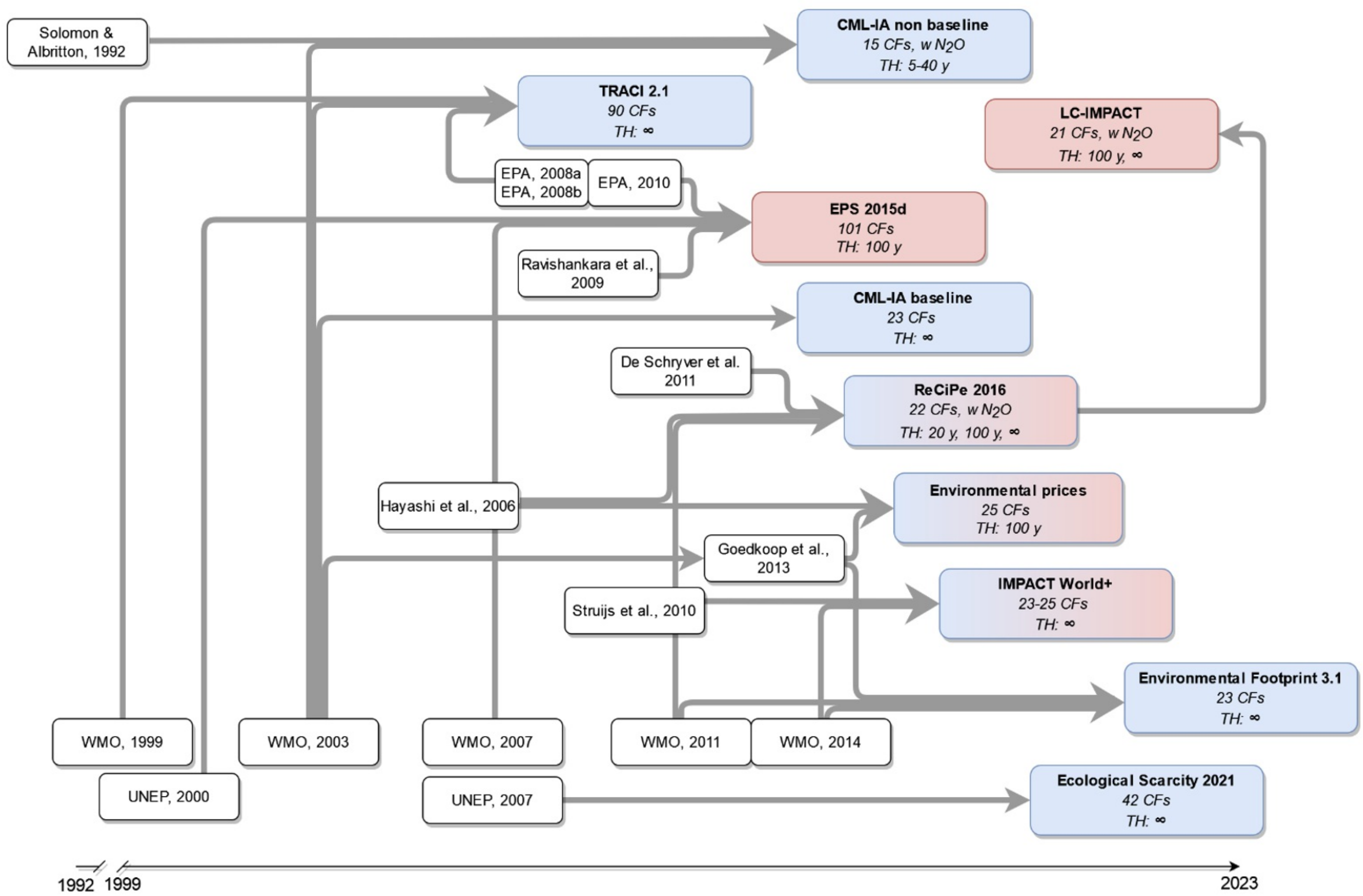

Figure 5. Overview of the Life Cycle Impact Assessment methods assessed in this review. White ovals represent data sources for ODP values and model assumptions. Blue refers to midpoint methods, while red represents endpoint methods. Full details on the impact assessment methods are given in Appendix A. CF = characterization factor, w= with, TH = time horizon, y = years, ∞ = infinite (De Schryver, 2011; EPA, 2010, 2008a, 2008b; Hayashi et al., 2006; Ravishankara et al., 2009; Solomon and Albritton, 1992; Struijs et al., 2010; UNEP, 2007, 2000; WMO, 2014, 2011, 2007, 2003, 1999).

While most LCIA methods follow the infinite time horizon approach, others also provide the impacts occurring during a finite time horizon, e.g., 100 years. For the CML-IA non baseline method (Guinée et al., 2002), time-dependent ODPs from Solomon and Albritton (1992) were used to estimate the impact after 5, 10, 15, 20, 25, 30, and 40 years. ReCiPe 2016 used the relationship from De Schryver (2011) to convert the steady-state ODPs to time-dependent ODPs as described by equations 14-15:

$$ODP_{t,x} = ODP_{inf,x} * \frac{F_{t,x}}{F_{t,\ CFC-11}} \qquad \text{Eq. 14}$$

$$F_t = 1 - e^{(-t-3) * k} \qquad \text{Eq. 15}$$

Where F_t is the fraction of the total damage caused by an ODS during the first t years, k is the removal rate of ODS in y^{-1}.

The reviewed characterization methods suffer from several limitations. Firstly, none of the reviewed LCIAs has yet implemented the newest ODPs by WMO (2022) and some methods are based on old WMO assessments that require updates (Figure 5).

In addition, most of the existing LCIA methods do not include all substances controlled by the MP. The last version of the UNEP Handbook for the Montreal Protocol (UNEP, 2020a) enlisted 93 CFs, sometimes expressed in terms of range, in the case of isomers. TRACI 2.1 (Bare, 2011), despite relying on relatively old sources, is the midpoint LCIA method, including the highest number of CFs (90). Ecological Scarcity 2021 (FOEN, 2021) follows, with 42 substances included. CML-IA baseline (Guinée et al., 2002), Environmental Footprint 3.1 (Andreasi Bassi et al., 2023; Fazio et al., 2018), Impact World+ (Bulle et al., 2019), and ReCiPe 2016 (Huijbregts et al., 2016) include a range of 22-25 substances. Lastly, the CML-IA non baseline method (Guinée et al., 2002) accounts for 15 CFs. It is this recommended to increase the coverage of ODSs in current LCIA methods, as ODPs are already available in the last version of UNEP Handbooks or WMO Assessments.

Another limitation is that substances not controlled by the MP are only sparsely included in LCIA methods. This review identified 32 substances not controlled by the MP but, instead, reported in WMO (2022). These substances can exert an impact, regardless of their presence in current international agreements. Only 5 of them were sparsely included in the LCIA methods. One example of such a substance is N_2O. As anthropogenic N_2O emissions, and not halocarbons, are the greatest source of human-induced stratospheric ozone depletion today (WMO, 2022), including their impact is of importance (Lane and Lant, 2012). From the reviewed LCIA methods, only ReCiPe 2016 (Huijbregts et al., 2016) and LC-IMPACT (Verones et al., 2020) include preliminary CFs for N_2O emissions.

Consideration of stratospheric aerosols is currently also lacking in characterization models, as shown in 6. However, they are known to affect stratospheric temperature, transport, and chemical reactions in the atmosphere (e.g., ozone destruction and formation) (WMO, 2022). Consequently, it is expected that large increases in stratospheric aerosols, for example, due to the large-scale deployment of rocket launches, stratospheric aerosol injection, and supersonic aircraft, would affect the ozone layer. Currently, the number of studies and model simulations on the effects of aerosols on ODSs and the ozone layer is limited (WMO, 2022), and existing studies show contradicting results (Tracy et al., 2022). These contradicting outcomes may be caused by the vast heterogeneity of aerosol particles, which is currently poorly represented in climate-chemistry models (WMO, 2022). Consequently, deriving CFs for aerosols is likely not yet feasible. More laboratory studies and climate-chemistry model simulations are required to understand the coupling between fluid mechanics and chemistry at aerosol particles (Tuck, 2021; WMO, 2022).

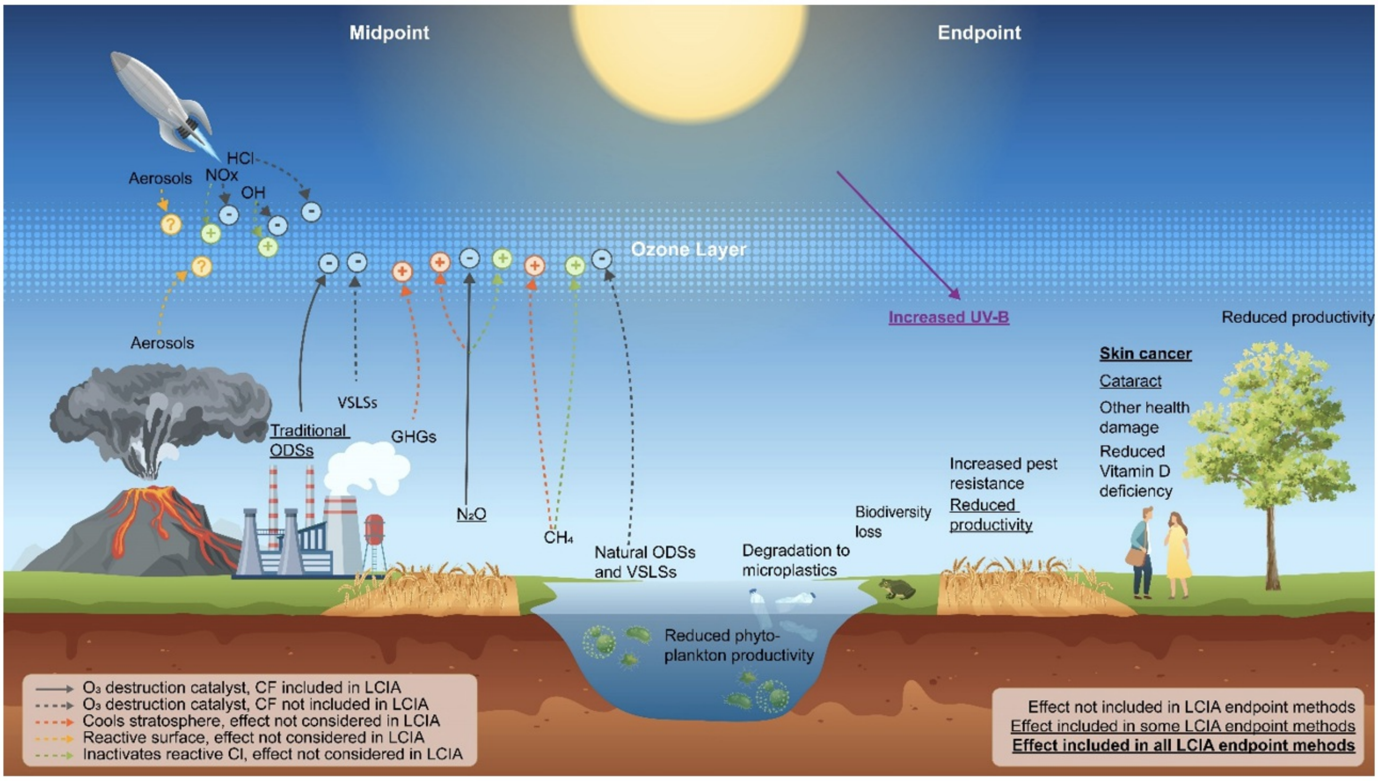

Figure 6. Summary of the limitations and challenges related to midpoint and endpoint characterization. Plus signs refer to positive effects on the ozone layer, minus signs to negative effects, and question marks to undecided effects. Illustration by: Francesco Gavardi.

Another limitation is the fact that ODPs are calculated using current atmospheric conditions, while the ODP of ODSs is dependent on these. In fact, atmospheric conditions and CH_4, CO_2, and halocarbon concentrations are considered the biggest sources of uncertainty of future stratospheric ozone levels (WMO, 2022). Considering future atmospheric conditions is important for accurate ODP assessments, particularly for N_2O, the biggest source of ozone depletion in the coming decades (Portmann et al., 2012; Ravishankara et al., 2009; Revell et al., 2015; Singh and Bhargawa, 2019). Under current atmospheric conditions, the ODP of N_2O (0.017 kg CFC-11 eq/kg) is in a similar range to many HCFCs, but a return to preindustrial chlorine concentrations, ceteris paribus, would increase it by 50% (Ravishankara et al., 2009). This effect can be explained by the reaction of NO_2 with ClO (Figure 1), fixing both the NO_2 and ClO in the inactive reservoir. In addition, CO_2 and CH_4 both have an overall positive effect on the N_2O ODP, and model simulations indicate that the ODP for a high climate change scenario (representative concentration pathway (RCP) 8.5) would be 200% higher than for a low climate change scenario (RCP 2.6) (Revell et al., 2015). However, these simulations did not consider the climate change-induced strengthening of the Brewer-Dobson circulation. This global circulation pattern consists of the upwelling of tropospheric air in the tropics, transport to higher latitudes, and downward transport at the poles, and its acceleration would reduce the stratospheric N_2O lifetime (Revell et al., 2015). In light of these effects, developing a set of climate change-dependent ODPs for N_2O is recommended using climate-chemistry models. Collaboration with atmospheric scientists will be required for the development of these CFs. As prospective LCI databases become more common in LCA practice, scenarios for the background and the characterization model must be consistent with each other and with existing climate change scenarios. It is therefore recommended to start the development of prospective CFs based on the existing shared socio-economic pathway (SSP) storylines and RCPs.

Progress in the development of endpoint characterization models has been slow in the past decades. ReCiPe 2016 (Huijbregts et al., 2016) and LC-IMPACT (Verones et al., 2020) used the damage functions developed for the Japanese LCIA LIME (Hayashi et al., 2006) in 2006. On the other hand, IMPACT World+ (Bulle et al., 2019) adopts the damage model proposed by Struijs et al. (2010), which improves the human health damage functions of Hayashi et al. (2006) by incorporating factors like future changes in population density, life expectancy, and skin color distribution. EPS2015d (Steen, 2015) uses excess cancer incidence and mortality rate estimates and cataract incidence reported by EPA 2010). Thus, it is evident that since 2010, there have been no significant advancements in ozone depletion endpoint characterization.

The existing endpoint characterization models suffer from several limitations. Notably, they exclude various potential effects on human health, such as immunosuppression, photo-aging, and solar keratosis (Bernhard et al., 2020; Hayashi et al., 2006; Struijs et al., 2010). Additionally, important factors like changes in behavioural adaptation patterns (e.g., sunscreen usage, sun exposure avoidance) (Bernhard et al., 2020) and positive effects like the reduction in vitamin D deficiency (Umar and Tasduq, 2022; Zerefos et al., 2023) are neglected. Similarly, ecosystem quality effects are currently disregarded despite their far-reaching consequences. For instance, increased UV-B irradiance negatively impacts phytoplankton growth and productivity, ultimately affecting ocean biological carbon fixation rate (Gao et al., 2018). However, formulating damage functions for phytoplankton poses challenges due to their complex interactions with ocean warming and acidification, which can be synergistic, antagonistic, or neutral (Liaqat et al., 2023). Moreover, plant morphological, molecular, and physiological attributes are also affected by increased UV-B irradiation (Liaqat et al., 2023). Depending on the species and the stressors induced by climate change, these effects can be either beneficial or detrimental. Therefore, comprehensive studies on the combined effects of increased UV exposure and climate change are essential [54]. Certain crops have been associated with decreased productivity at higher UV-B levels. On the other hand, it was shown that adaptation mechanisms developed by plants under high UV-B stress have made them more UV-B stress-resistant (Mmbando and Hidema, 2021) and more resistant to biotic stresses (Mmbando, 2023). Differences in UV-B resistance between species can generally lead to ecosystem changes (Hyyryläinen et al., 2018) and biodiversity loss (Bernhard et al., 2020). For example, amphibians are particularly sensitive to the immunosuppressive capacity of UV-B, leading to a higher disease susceptibility and extinction rate (Cramp and Franklin, 2018). Many other effects exist, such as the enhanced photo-oxidation of plastics, increasing the production of microplastics (Andrady et al., 2022).

The existing limitations for assessing ozone depletion at the midpoint and endpoint level are summarized in Figure 6. Given these numerous limitations, it becomes evident that the current midpoint characterization models must be further developed, and endpoint characterization models are not mature enough for recommendation [16] since they capture only a fraction of the damage induced by ozone layer depletion. Including all these effects presents a daunting challenge, requiring substantial amounts of additional data and sophisticated modelling techniques to account for the synergistic and antagonistic effects with other impact categories, such as climate change and acidification.

4.3.2. Normalization and weighting

Normalization and weighting are optional steps in LCA that can be applied to increase the interpretability of the results. Normalization expresses the characterized results relative to a reference state, for example, national or global emission inventories, while weighting offers a mechanism for addressing trade-offs among distinct impact categories (Hauschild et al., 2018).

Most LCIA methods offer normalization factors derived from outdated global inventories dated before 2010 (Table A1 in Appendix A). EF 3.1 provides the most recent normalization factors based on a global inventory for 2010. However, it should be noted that the completeness of this inventory is estimated to be below 30% (Crenna et al., 2019). Furthermore, the current normalization factors lack the inclusion of N_2O emissions and other substances that have not been incorporated into existing impact assessment methods. Consequently, currently, available ozone depletion normalisation factors do not yield scientifically accurate results. Improving normalization factors is recommended, as it will allow comparing the contributions of different sectors (e.g., agriculture vs. space travel) to ozone layer depletion. In this regard, the GLAM initiative will publish an updated normalisation reference using recently published data. ODS emissions data for 2022 is sourced from the WMO 2022 Scientific Assessment of Ozone Depletion. Unlike prior studies using emission data differentiated by individual countries (Laurent et al., 2011; Sleeswijk et al., 2008), the GLAM inventory uses global emission data, which are more consistent. Supplementary N_2O emissions data were obtained from EDGAR v.7 (EC and JRC, 2021) and Minx et al. 2021).

Three different weighting methods are present in the reviewed LCIA methods. Ecological Scarcity 2021 provides distance-to-target weighting factors, which express the normalized results relative to the Swiss policy targets for 2040. Consequently, this method is not useful outside of Switzerland. EF 3.0 developed combined general public and expert panel-based weighting factors. Ozone depletion ranked middling for all human health-related impacts according to the general public, while the LCA expert panel deemed it the second-least significant impact category. However, the drawback of the weighting factors developed by these panels is that they represent the panel's *perception*, rather than the absolute hierarchy of ozone depletion's significance. Finally, Environmental Prices and EPS2015d each adopt monetary weighting factors, albeit founded on divergent valuation methodologies. EPS2015d employs a willingness-to-pay framework, while Environmental Prices integrate damage-cost assessments. The limitation common to all the reviewed weighting methodologies lies in their susceptibility to fluctuations over time and geography, owing to the dynamic nature of policies, perceptions, and prices. Therefore, the authors advocate for the development of weighing approaches that have a global scope. Such global weighting schemes are currently under development in the GLAM initiative using conjoint analysis and multi-criteria decision analysis, using a global survey of more than 3,000 respondents from countries spanning various income levels. Recent developments (Bjørn et al., 2015; Sala et al., 2016; Vargas-Gonzalez et al., 2019) that aim to develop weighting factors based on planetary boundaries (Steffen et al., 2015) could be particularly relevant.

Although their scientific robustness is often questioned, normalization and weighting are considered valuable for decision-making (Pizzol et al., 2017) and they may help answer the question: is ozone depletion still a relevant impact category today? This could be done by performing an "LCA of the world", similar to (Bulle et al., 2019), but with updated LCI databases, characterization, normalization and weighting factors.

4.4. Interpretation

The interpretation phase relates to each of the previously defined phases and comprises a completeness check, a consistency check, a sensitivity analysis, the identification of key issues, and the communication of conclusions, limitations, and recommendations (Laurent et al., 2020). The identified challenges in this review show that the inventory phase and the LCIA phase are severely lacking in completeness. Therefore, in the interpretation phase of ozone depletion impact results LCA practitioners must consider these limitations. The strategies proposed in this review are summarized in Figure 7.

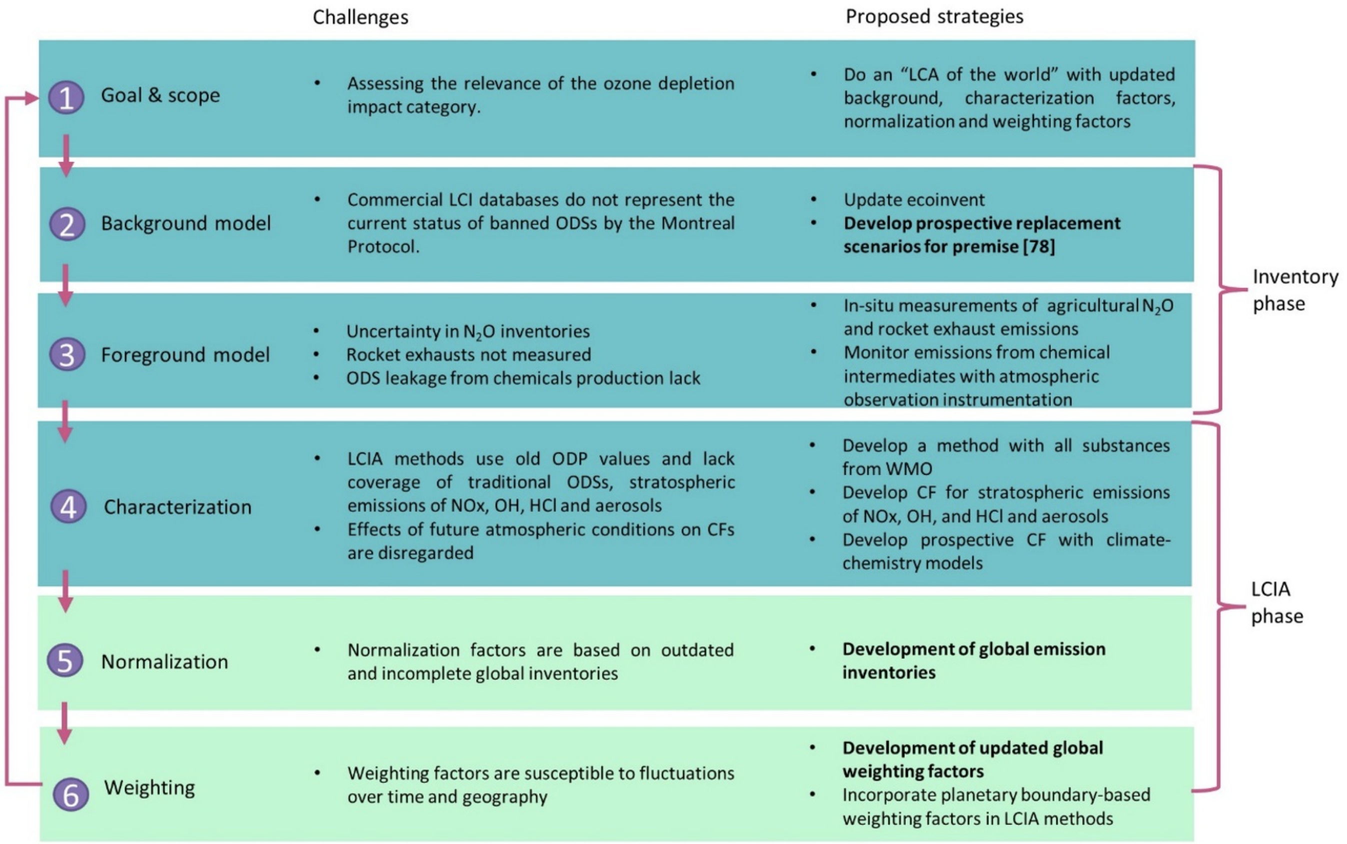

Figure 7. Summary of challenges related to ozone depletion assessment in LCA. Light green steps are optional. Future work in bold is ongoing.

5. Outlook and conclusions

This review has shown that the currently available LCA ozone depletion practices are unsuitable for supporting decision-making. The combined effects of outdated background databases and incomplete impact assessment methods must be further investigated to understand their full scope. Here are some strategies that could be developed to address the identified shortcomings.

Foremost, in the short term, a thorough review of commercial LCI databases is imperative to validate the accurate representation of the ODS phase-out mandated by global environmental legislation. Additionally, the inventories of key contributing sectors must be revised, paying special attention to the leakage emissions of ODSs from chemical precursors and intermediates. In instances of inaccuracies, efforts should focus on identifying and rectifying outdated datasets. However, a one-time database update would not be sufficient, as the phase-out of ODSs and their substitutes is still in progress. Therefore, regular updates are required. Another approach is the development of a prospective background scenario to account for ODS substitution, considering the approach taken in premise (Sacchi et al., 2022). Premise is a tool that creates prospective versions of a given LCI database. It does so by systematically applying modifications to LCI inventories from key energy-consuming sectors to account for future developments based on scenarios provided by integrated assessment models or the user. The suggested ODS phase-out scenario would have temporal and geographical differentiation, considering varied country-specific phase-out timelines and the emission lag associated with existing ODS stocks. The envisaged background scenario holds the potential to substantially influence the climate change and ozone depletion impacts associated with many product systems.

Additionally, an updated LCIA method needs to be developed that includes the CFs of the latest WMO assessment (WMO, 2022) for all ODSs. In the longer-term, different sets of CFs, considering different future atmospheric conditions, could be developed. This should also encompass CFs for N_2O and stratospheric emissions for NOx, HCl, and OH, necessitating collaboration with atmospheric scientists to address the complexities associated with varying future atmospheric conditions. A harmonious relationship between background and characterization scenarios and alignment with existing climate change scenarios like shared socio-economic pathway (SSP) storylines and representative concentration pathways (RCPs) is pivotal. Furthermore, exploration into the inclusion of CFs for stratospheric aerosols in LCIA methods warrants dedicated research efforts.

Recent advancements in experimental data and methodologies have also led to the development of alternative metrics for evaluating ODP (WMO, 2022). For instance, a new metric was recently proposed [79] called Stratospheric ODP (SODP), only referring to the ozone depletion happening in the stratosphere. This concept is more suitable for application to VSLSs. In the case of CF_3I, for example, the SODP is about zero because almost all the ozone depletion caused by CF_3I occurs in the lower troposphere. Since the ozone in the troposphere has increased over the last century due to human activities, the action of CF_3I could paradoxically be beneficial to the environment; in fact, tropospheric ozone formation harms human health, as the presence of a dedicated impact category in the LCIA methods indicates. Therefore, the original ODP concept, which focused on the stratospheric ozone but calculated concerning the total ozone column, could inflate the concerns about the impact of VSLSs on human health. In the future, this concept should be considered in the midpoint calculation methods.

More generally, this work showcases the importance of analysing interlinkage challenges between impact categories. Climate change, in particular, exhibits both synergistic and antagonistic relations with ozone depletion and potentially with other impact categories. Therefore, it is recommended that specific challenges of the other impact categories be reviewed rigorously, both individually and collectively. In light of the uncertain trajectory of climate change, the development of climate scenario-dependent characterization and normalization factors is advocated. These advancements empower LCA practitioners to evaluate environmental performance across a spectrum of future conditions, thus facilitating robust decision-making within our inherently uncertain world.

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